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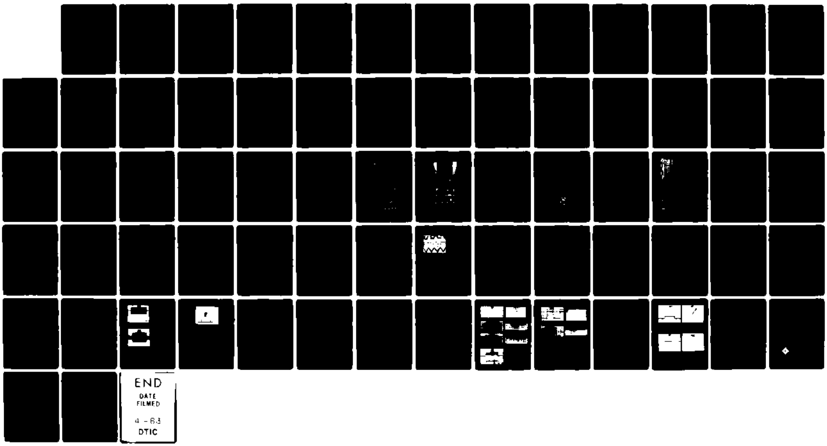

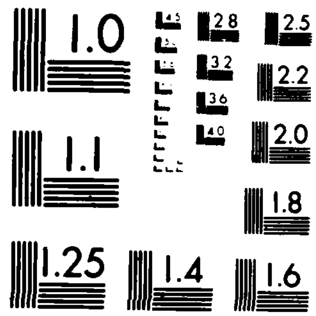

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Chemical, mechanical (goemetrical), electrical and thermal stability parameters of the metal-oxide (insulator)-metal (MOM of MIM) diodes based on point contact and discontinuous metal film structures have been examined exhaustively for diode stabilization and optimization of performance for mm wave and near infrared laser detection and mixing. Preliminary observations and analysis have indicated possibility of achieving long term stability with little loss of the ultrahigh frequency of operation and ultrabroad bandwidth of these devices. As instability

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is greatly reduced, fundamental physics of the conduction mechanisms and their regimes of operation should then be unambiguously analyzed and identified. The techniques acquired have led to the initial fabrication of thin film chip diode arrays for for efficient detection and mixing.

FABRICATION AND STUDY OF BROADBAND MIM DETECTOR-MIXER

FINAL REPORT

DR. CHUNG YU

MAY 15 1980 TO DECEMBER 1982

U. S. ARMY RESEARCH OFFICE

DAAG 29-80-C-0117

NORTH CAROLINA AGRICULTURAL AND TECHNICAL
STATE UNIVERSITY

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ABSTRACT

Chemical, mechanical (geometrical), electrical and thermal stability parameters of the metal-oxide (insulator)-metal (MOM or MIM) diodes based on point contact and discontinuous metal film structures have been examined exhaustively for diode stabilization and optimization of performance for mm wave and near infrared laser detection and mixing. Preliminary observations and analysis have indicated possibility of achieving long term stability with little loss of the ultrahigh frequency of operation and ultrabroad bandwidth of these devices. As instability is greatly reduced, fundamental physics of the conduction mechanisms and their regimes of operation should then be unambiguously analyzed and identified. The techniques acquired have led to the initial fabrication of thin film chip diode arrays for more efficient detection and mixing.

INTRODUCTION

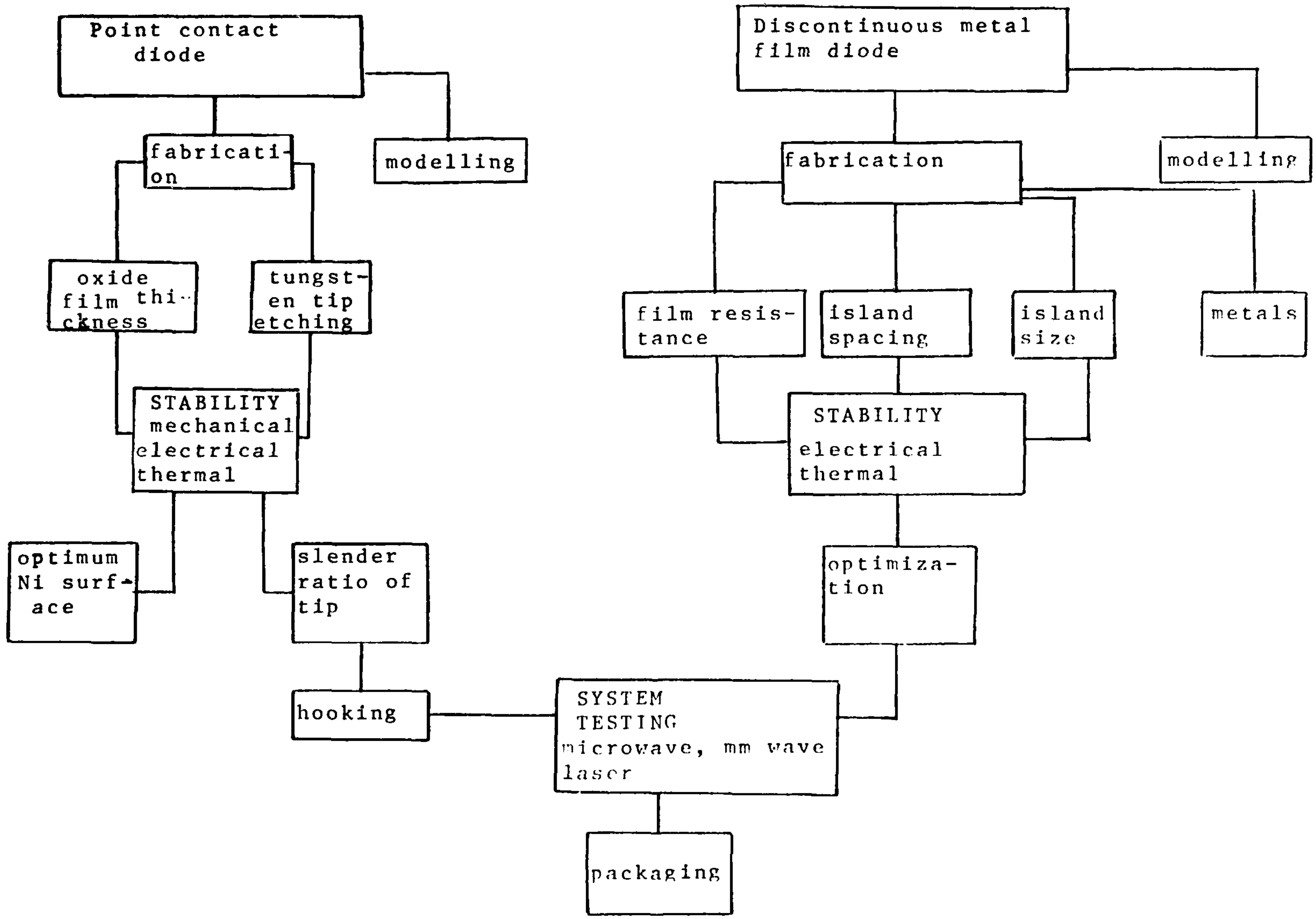
The generally accepted tunnelling process as the dominant conduction mechanism and the majority carrier aspect of such a conduction process have been widely demonstrated by the ultra-high frequency of operation and ultra-broad bandwidth of the metal-oxide-metal (MOM) or metal-insulator-metal (MIM) diodes. The point contact version has been reported to perform mixing in the near infrared with bandwidths of the order of over a hundred GHz[1]. Despite its tremendous bandwidth and excellent antenna property, the MOM point contact diode has often been faulted for its inherent mechanical, thermal and electrical instabilities and non-reproducibility in fabrication. These undesirable features have hampered its wider application. Alternate thin film versions have thus been considered by us and a number of research groups. The photolithographic thin film diode on substrates has been demonstrated[2] to overcome mechanical instability only. The discontinuous metal film version[3] with greater ease of fabrication and potential to overcome all the above instabilities is being seriously considered by us.

The metals, their geometrical arrangement and shape, and the naturally grown oxides must be explored exhaustively in order to arrive at MOM or MIM structures with optimum stability and response. In the point contact version using sharp tungsten whisker in contact with the naturally grown oxide on a nickel post, both the geometric shape of the whisker tip and nature and thickness of the oxide layer must be examined. Studies have led to the establishment of an undamaged hooked tip with an optimum slender ratio and optimum oxide thickness.

In the discontinuous metal film, island spacing, size and island material with different work functions are the parameters that ultimately determine diode performance and stability.

Thus, the performance and stability of these diodes are extremely dependent on the chemical, mechancial, electrical and thermal properties of the materials that compose the diode: the metals and their oxides determine the chemical stability of the oxide or insulator layer and thickness; the geometric shape of the tungsten whsiker tip in the point contact version determines the amount of penetration of the tip into the oxide layer and thus the ultimate oxide thickness between metals and the amount of hooking of the tip. This aspect of geometric shaping for stability has been extensively explored; oxide thickness, island spacing and size naturally determine the electrical resistance of the diode, which holds the key to diode performance, stability and immunity to puncture due to accumulated electrostatic charge.

STATUS OF WORK ON MOM STRUCTURES AS DETECTOR AND MIXER DIODES



TUNGSTEN-NICKEL MOM POINT CONTACT DIODE STABILITY PARAMETERS

CHEMICAL STABILITY PARAMETERS

An outstanding characteristic of the tungsten is its well known high melting point of 3410^{o}C; its extremely strong atomic cohesion also accounts for its mechanical strength and small thermal expansion. These properties are thus utilized for mechanical stability of the tungsten whisker tip as the point contact of the diode, especially under intense focused laser radiation. Furthermore, tungsten is not oxidized to a significant degree in the atmosphere up to 550^{o}C and remains so up to 1000^{o}K reached under normal laser irradiation. Even at higher temperatures, no considerable contribution comes from the inside oxide layer due to the metallic properties of W_4O_{11} forming the outside oxide layer.[4,5,6]

The tungsten whisker is generally etched from polycrystalline wire, which is usually drawn with preferred grain orientations along the wire axis. Electrolytic etching of the wire produces tips much smaller than the grains so that the tip forms a single crystal consisting of (111) faces with a common 110 axis along the whisker direction .

In the tungsten-on-nickel MOM diode, the insulating layer that forms the tunneling barrier is thus mainly the nickel oxide, which is one of the best insulators in nature with an electrical resistivity of 10^{15} ohm-cm. Oxide layer thickness is approximately 6-8 Å by electropolishing [7] and 9-12 Å by anodic oxidation [6] and much greater at elevated temperatures .

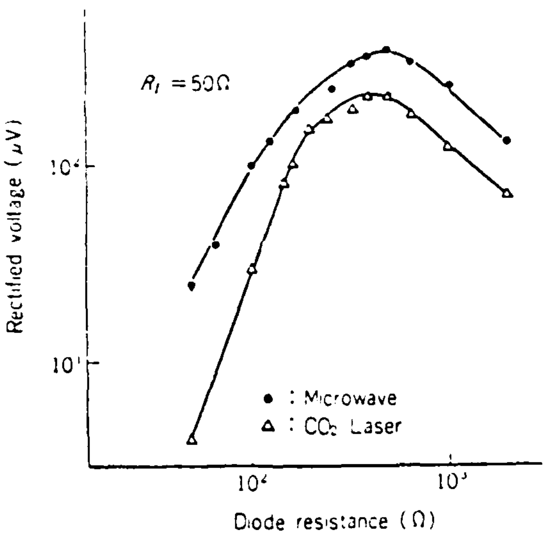
Nickel oxide layers have also been formed by initial mechanical polishing in a dilute viqa solution, then etched with phosphoric acid and potassium dichromate to achieve a clean surface. The surface oxide is then formed by short baking at 450°C. Oxide thickness varies with the duration of oxidation. Oxide thickness formed in this manner ranges from 5 Å to 1500 Å. The dry air-formed oxide film at room temperature is also 6-8 Å in thickness and is basically stoichiometric NiO[8].

However, it has been shown theoretically[9] and experimen ·ly[10] that diode responsivity increases several orders of magnitude with sing insulator thickness, as a matter of fact, reaching a maximum at 12 Å[10].

Rectification efficiency has been shown[10] to be extremely sensitive to work function differences between the two metals so that dissimilar metal diodes are superior. It has also been suggested[11] that geometrical asymmetry of the diode improves rectification for any metal combinations. Thus, a gold whisker on a gold base proves to be the most efficient detector at 75 GHz , but cannot be used as frequency mixer and harmonic generator in the infrared.

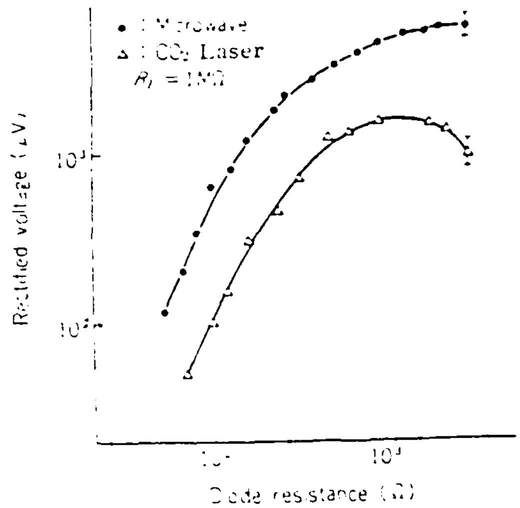
It is well known that MOM point contact diodes present great difficulty in control of contact pressure. It is reported[8] that detection sensitivity is highest when the contact pressure is very low. Diode resistance is a strong function of the contact pressure.

These circuit limitations have also been demonstrated by the dependence of detection sensitivity on the load resistance in the diode circuit as shown below.



Variation of rectified voltage with diode resistance

Fig. 1



Variation of rectified voltage with diode resistance.

Fig. 2

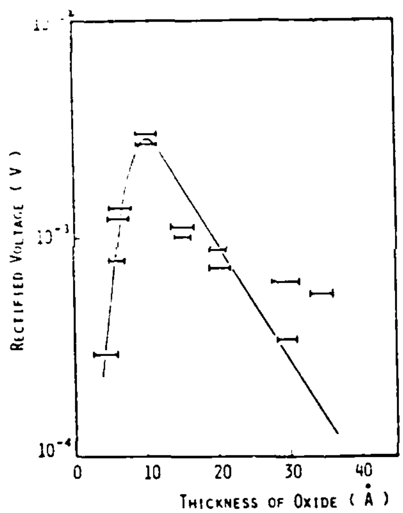
DEPENDENCE OF CONDUCTION MECHANISM BETWEEN METALS ON OXIDE FILM THICKNESS

Tunneling and Schottky emission are usually the processes quoted to explain electron conduction in an MOM diode. Thus, we have

$$J_S \sim T^2 \exp(+a\sqrt{V}/T) \quad \text{for Schottky emission, and}$$

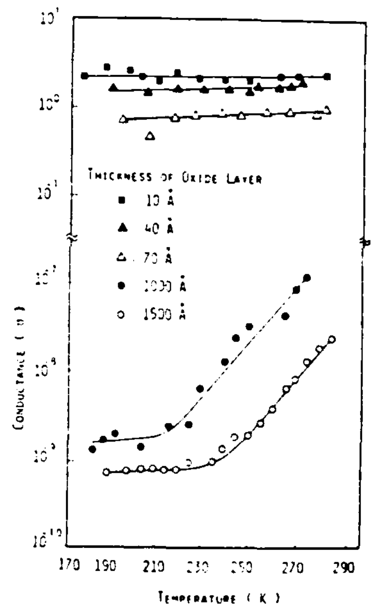
$$J_T \sim V^2 \exp(-b/V) \quad \text{for tunneling.}$$

The current density due to Schottky emission is thus an exponential function of temperature, while tunneling current density is essentially temperature independent. The operating ranges of these two conduction processes are well illustrated in the figures below [1]



Relationship between the detected voltage V_{RMAX} and the oxide thickness on the nickel post.

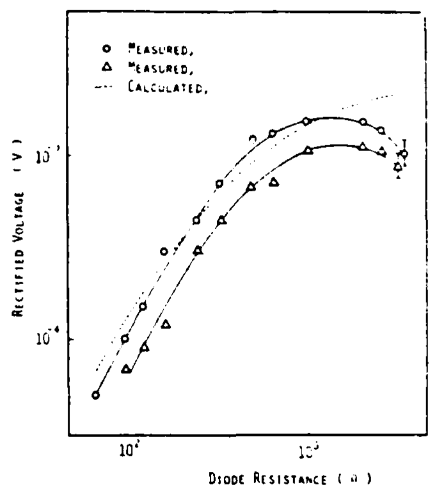
Fig. 3



Current-temperature characteristics of the diodes with various oxides.

Fig. 4

These results seem to indicate that rectification is quite sensitive to oxide film thickness and the two conduction mechanisms play their dominant roles in different ranges of oxide film thickness. Thus, tunneling is dominant for thin oxide films and Schottky emission is dominant in thick oxide films at elevated temperatures. We will thus confine our considerations to thin films for the fabrication of a temperature dependent diode. Since oxide film thickness is closely related to diode resistance, which in turn determines the amount of rectified voltage from the diode as shown below[3], oxide film thickness and the maintenence of the constancy of film thickness are the key to the fabrication of an optimum and stable diode.



Dependence of the detected voltage on the contact pressure. Oxide thickness on the nickel post; 10 Å.

Fig. 5

From our experience, this so called contact pressure variation is nothing but variation in oxide film thickness due to penetration of the whisker tip into the deposited oxide layer. Thus, increase of contact pressure causes deeper penetration and thus lower diode resistance and vice versa. Hence, the authors noted that the best response occurred when the whisker was just separate from the nickel post or minimum penetration since 10 A is the optimum thickness for the rectified voltage.

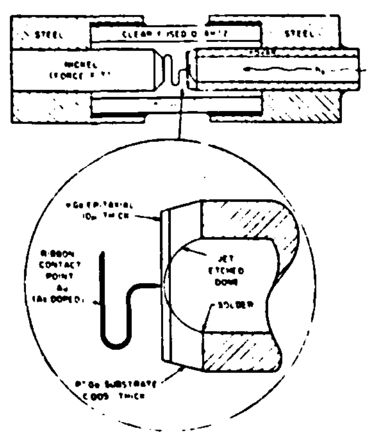
So far, only dry air oxidized films have been used in our experiments and they are less than the optimum thickness. The improvement in diode stability is thus rather impressive, considering that we have been operating mostly on the significantly steep slope of the rectified voltage versus oxide thickness curve. It is thus our intention to grow thicker films so that we operate the diode at the optimum thickness level with a broad peak. This will further reduce the sensitivity of the diode to oxide thickness variation, resulting from many sources such as mechanical vibrations, thermal expansions.

MECHANICAL STABILITY PARAMETERS

CONTROL OF OXIDE FILM THICKNESS AND CONTACT PRESSURE AS KEY TO DIODE STABILITY

In the case of contacting a sharp whisker tip with an oxide layer at exactly the optimum thickness, there will be certain amount of stability achieved due to the flat top of the rectified voltage output versus oxide film thickness curve. Thus slight variation in the thickness between the two metals will not lead to singificant variation in the rectified voltage. However, for such an arrangement, the sharp tip is at the point of barely making contact with the oxide film, so that any vibration induced variation in the separation between the tip and the post will lead to periodic breaking of contact and thus open circuit at the vibration frequency. Such sensitivity to vibrations cannot be tolerated. Such a configuration involving a sharp tip is also susceptible to oxide surface variations.

Such arrangement has been made in some MIS diodes, typically as shown below[12]. Great pains have been taken to ensure constancy of contact and contact pressure. Even if we can be convinced of the mechanical stability of such a diode, we cannot believe such a diode can be used under reasonably high power radiation, when thermal expansion must be taken into account, or even without irradiation except room temperature variations. It must be noted that we are concerned about physical distance variations of no more than 1-2 Å. Then, there is the question of very slight mechanical vibrations of 1-2 Å amplitude. No doubt the high electric field at the sharp tip due to accumulated static charge is often observed to puncture the oxide layer.



Cross-sectional view of encapsulated point-contact photodiode.

A natural step that can be adopted to alleviate most of the above difficulties is to alter the contacting arrangement. A thicker than optimum oxide layer can be grown, and the sharp tip is allowed to penetrate the oxide layer to reach the optimum thickness. In the process of penetration the sharp whisker tip is expected to hook, creating a reasonably large contact area inside the oxide film and providing via the hook some measure of a cushioning effect. The key of the success of this scheme lies in the controlled etching of the sharp whsiker tip to achieve a so called optimum slender ratio - ratio of the tapered shaft length to the tip diameter. An optimum slender ratio is defined as the shape parameter that will ensure hooking of the tip with minimum damage to the tip and minimum diversion of the tip from the elbow or contact area. This thus calls for careful reexamination of the electrolytic etching process of the tungsten whisker.

TUNGSTEN WHISKER TIP DEFINITION

It is through the careful and consistent definition of the physical state : damaged, blunted, hooked and undamaged, of the whisker tip of the MOM point contact diode that we have been able to arrive at a single design parameter of the undamaged hooked tip coined by us as the slender ratio. The shape of the hook controls the stability of the diode with no significant loss in tip responsivity.

The slender ratio is designed by reexamining systematically the fabrication process. This process involves two steps: etching of the tip and contacting of the tip with the nickel post.

At a certain voltage between electrodes and KOH solution concentration, the single factor that determines the slender ratio is the depth of immersion of the tungsten wire in the solution. The simultaneous etching of the portion of the wire covered by the miniscus and the submerged portion, with the latter providing an additional conduction path served to prolong miniscus etching in proportion to immersion depth up to a certain depth.

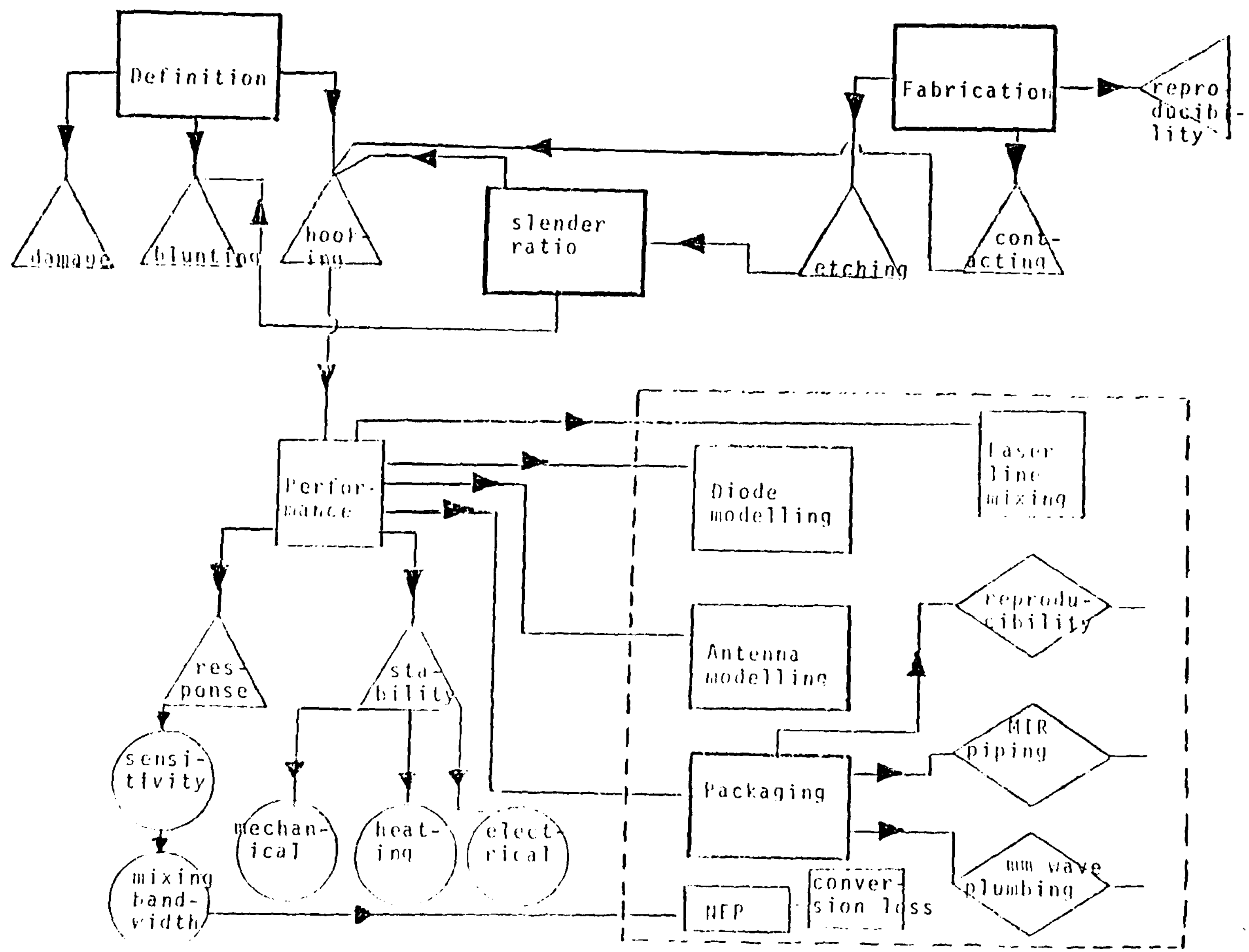
Tips with different slender ratios are then mounted for contact with the nickel post. Hooks are formed during this contacting process. The shape of the hook is determined by the slender ratio and the carefully applied contacting stress or pressure. An appropriate amount of stress is defined as that which achieves diode stability and reasonable sensitivity. Excessive stress will produce excessive hooking in very slender tips, i.e., tips of large slender ratio, and blunting or damage in stout tips or tips with small slender ratio.

Diode stability is classified according to origin as: mechanical, heating and electrical. The unique feature of the hook provides some cushioning for mechanical vibrations, a free end for thermal expansion and contraction, and a rounded bend in the oxide junction area and thus less susceptibility to electric charge buildup and puncture. All these conjectures have been proven to be true.

With proper hook shaping, sharp tip field enhancement in the junction area is not significantly degraded if the sharp tip is not too far away from that area. In V band mixing experiments, the MOM diode has demonstrated its superior bandwidth at this stage of fabrication to commercial units.

It is thus believed that with some more work in packaging, the point contact MOM diode may prove to be a field applicable device with sensitivity comparable to MIS units and bandwidth not matched so far.

PROCEDURE OF TUNGSTEN TIP DEFINITION, PREPARATION AND SYSTEM TESTING



The standard electrolytic, self-terminating process for etching the tungsten wire in 3N KOH solution was adopted . The applied ac voltage, conduction current and depth of tip immersion were carefully monitored and controlled. The etching process was scrutinized under a 100 x microscope. Although it is generally believed that the miniscus around the immersed wire determines the profile of the etched tip, we found that wire immersion depth was, within a certain range, also a controlling factor by proving an additional conduction path, which prolonged the etching process. Thus, deep immersions produced long, slender tips, while miniscus etching dominated for shallow immersions. leading to sharp tips with shart shafts. The tip profile was conveniently characterized by a slender ratio, i.e., the ratio of the shaft length to tip diameter. A tip with optimum slender ratio is defined as one that will penetrate the oxide layer with minimum damage and sufficiently to produce high responsivity and be minimally bent so as not to increase the contact area appreciably.

The bent tip has often been encountered by workers in this field, but viewed negatively because of possible damage imparted on it, it uncontrollability and the possibility of increased contact area, thus increased capacitance. However, it has also been argued that the simultaneous reduction in diode resistance may compensate the increase in capacitance so that degradation in diode performance is debatable. Uncontrollability can definitely be removed by controlling the slender ratio. It is on this basis and our preliminary experimental observations of no noticeable reduction in responsivity that we decided to define and investigate systematically

the possibility of exploiting this hook feature to improve diode stability.

Absence of the sharp tip in the contact region will certainly reduce vulnerability to electrical shocks. Spring action of the hook cusions quite well mechanical vibrations affecting the free standing whisker. Susceptibility to heating is present in varying degrees in the metal island, printed circuit and free standing versions, with the last two affected the most. This is almost nonexistent in the hooked-tip version, in which thermal expansion and contraction occur at the free end and not in the junction area.

Most of these conjectures were confirmed in our experiments. Thus, the shape of the whisker tip characterized by its slender ratio can be controlled and reproduced through strict control and maintenance of the etching parameters. The ratio is the governing factor of the eventual hook contour following tip penetration into the oxide layer. There is trade off between stability and responsivity only in the sense when the tip is excessively hooked because of too slender a shaft, resulting in insufficient penetration of the oxide layer and excessively large contact area. The range of slender ratios for acceptable performance is rather large. Many whiskers were fabricated and tested at X band, V band and at CO_2 laser frequency on an optical table purposely without provision for removal of normal room vibrations.

Typical experimental data on sharp tip detection in the infrared are presented. The improvement in stability once the hook was formed was dramatic. We have yet no long term stability data (over days or months), but our rather casual handling of the diode mount and repeated observation of stable detection with a hooked tip, were convincing evidence of possible long term stability.

Responsivity improved as contact pressure was reduced by no more than two to three fold, while instability increased significantly. This may be indicative of the RC independence of diode performance to first order so that the hooked contour should be a sound basis for a stable device.

Creation of a free end is the single most important feature of this improved diode, enabling it to avert the major heating instability resulting from thermal expansion of the whisker tip. Heating effect is definitely present as evidenced in the extreme case of an unchopped laser beam and the observation of a regular pulse train due to making and breaking of contact of the whisker with the nickel post, the former due to thermal expansion of the whisker and the latter, its retraction after heat sinking by the post. This phenomenon was not observed in the case of the hooked tip. Departure of the detected signal from a rectangular waveform cast doubt on the true nature of detection, such as possible heat induced diode resistance variation at the chopper speed. This was removed by changing chopper speed and observing no significant change in detected signal amplitude. This form of instability is unavoidable at high incident powers, but should play no part in the device as a mixer.

Another often reported and analyzed effect is polarity reversal, which, interestingly enough, was not observed with the hooked tip. It was frequently encountered during the early part of our work with the sharp tip and again in the case of the hooked tip only when it was withdrawn to the point of breaking contact. This suggests that polarity reversal, though may be of fundamental interest, is another form of instability associated with the sharp tip.

These improvements in stability have been demonstrated in the free standing point contact diode, and should be applicable to the printed circuit version. The removal of the effect of thermal expansion of the tip is the most important feature. Thus, not only can this device be used as a high power infrared detector, but also as an efficient and stable mixer, where high power stability is essential, since its efficiency is proportional to local oscillator power level. The tremendous bandwidth has also been recently reported at 170 GHz[1] .

Possibility of long term stability study is being considered since it involves strict maintenance of environmental conditions, such as vibrations, room temperature, draft conditions, etc. The biconical antenna model of the long wire version also needs revision.

ALTERNATE MIM STRUCTURES

Photolithographic printed circutis [2] have been proposed as alternate MOM structures. No particularly encouraging results have been reported. These MOM structures deposited on glass substrates will remove mechanical instability. However, these are essentially metal-insulator(substrate)-metal devices since no fabrication of a 12 A oxide film thickness is possible with current technology. Such diodes thus tend to have very low responsivity. Furthermore, the sharp tip structure is still present so that they are again not immune to thermal and static shock instabilities.

We have so far conducted substantial amount of work towards the development of a discontinuous metal film MOM diode by sputtering various types of metals onto a glass substrate at very short durations. According to theory [3], metals islands are formed on the substrate with separation between islands highly dependent on the deposition rate, and achieving distances from 0 to 40 Å. With the understanding gained from the point contact diode work, we believe we can achieve the optimum island separation of 12 Å. Other parameters can also be employed such as the use of dissimilar metals or metals with naturally very thin oxide layers of high resistivity. Some of our preliminary experimental results are given below.

CHARACTERISTICS OF SINGLE-LAYER DISCONTINUOUS METAL FILMS

In the initial phase of continuous metal film deposition, the deposited film structure is discontinuous, consisting of a large number of islands on a substrate and growing in size as metal atoms accumulate on the substrate. In films with high density of small islands, direct tunneling will be the principal conduction mechanism. However, as the distance between islands and the sizes of the islands are increased, the conduction process becomes complicated. Thus, other models of conduction have been proposed, such as conduction via impurity levels of the substrate material, thermal excitation of electrons in the islands and thermal emission of electrons. Domains of operation of the various conduction mechanisms have thus been proposed as shown below.

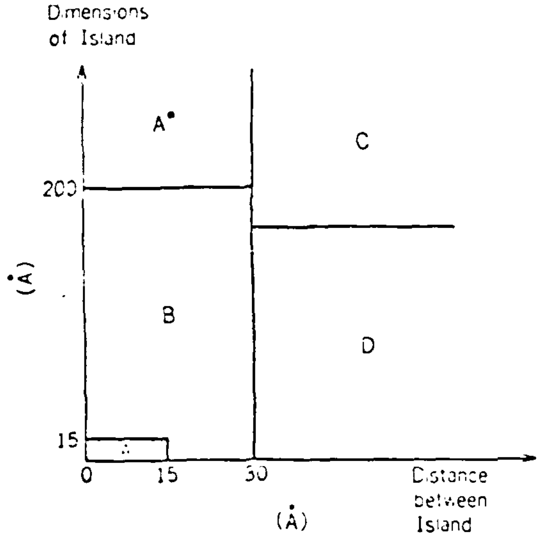


Fig. 6

A, A* : Direct tunneling effect
B : Tunneling effect assisted by thermal excitation
C : Tunneling effect through substrate
D : Thermal electron emission

Electric conduction mechanism of island structure thin metal films.

A discontinuous metal film corresponding to region A, where direct tunneling is the dominant conduction mechanism, consists of a large number of M-I-M junctions connected in series and parallel. When an electromagnetic wave is incident on such an array, signals detected by individual junctions are summed. The proper choice of arrays can ensure a large output signal, and thus compensates the absence of the long wire antenna of the point contact diode. Such a structure is mechanically stable, and with proper design (to be discussed) can also be thermally and electrically stable.

The standard vacuum deposition technique is employed. Various metals were tested with no detection on Ni and Al films due possibly to the ready natural oxidation of such islands, which increases the spacing between islands. Discontinuous gold films are successful, but film resistance is unstable. However, both large and small islands are present, with the latter acting as noise sources.

In our attempt to construct discontinuous metal film diode as high frequency detector with low noise, high sensitivity and stability, it stands to reason to fabricate films in which direct tunneling is the dominant conduction mechanism. It is known that films of palladium or platinum-palladium deposited on glass substrates provide stable islands of extremely small size. However, such films normally present high sheet resistance of several meg-ohms and low sensitivity. Such high diode resistance is easily loaded by external detection circuits .

Multi-layer film structures have therefore been suggested, consisting of palladium-platinum film deposited on gold discontinuous film. Gold film is first deposited to give a film resistance in the hundred kiloohm range, and this is reduced by Pt-Pd film down to the ten kiloohm range. The Pt-Pd islands are observed to be situated between larger gold islands. Such a multi-layer is stable and demonstrates improved noise property, sensitivity and life.

The relationship between film resistance and detection sensitivity is shown below. The drop in sensitivity in the low resistance range is obviously due to the formation of a progressively continuous film, and that towards the high resistance range due to increasing departure from the direct tunneling domain. There is also the circuit condition that very little signal can be extracted from the diode, which has either extremely low or extremely high internal resistance.

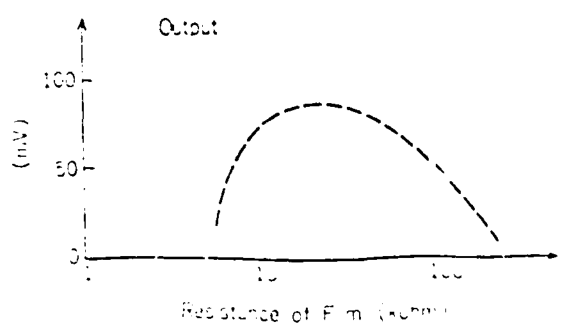


Fig. 7

Sensitivity vs. resistance of thin film.

STABILITY PARAMETERS OF THE DISCONTINUOUS M-I-M FILM

MECHANICAL STABILITY - this is considered to have been overcome by the deposition of such films on glass substrates.

THERMAL STABILITY - If film deposition is such that the diode will be operating in the direct tunneling region, the conduction current is not a function of temperature. However, under intense irradiation either by microwaves or the laser, there will be some thermal expansion of the metal islands. Variations in inter-island spacing can be extremely significant due to its extremely small dimension. It will therefore be quite advantageous to select a spacing such that we are operating on the flat top of the detection sensitivity versus island spacing (or diode resistance) curve. The diode should then be able to tolerate certain amount of spacing variations without serious effects on the detection sensitivity.

FABRICATION STABILITY OR REPRODUCIBILITY - The above flat top region of operation of the diode will also lead to larger tolerance in film deposition.

SUSCEPTIBILITY TO ELECTRIC SHOCKS - Optimum inter-island spacing will also lead to lower susceptibility to puncture of insulator layer due to accumulated electrostatic charge.

STABILITY TO FILM AGING - This is caused either by instability of the metal, or the insulator layer between islands. Thus, metal combinations will be explored which give best stability of both of these factors. Metals with very stable natural oxides will be studied again since the optimum flat top response is situated at an inter-islans spacing larger than the thickness of such oxides.

DISCONTINUOUS MIM FILM DIODE PERFORMANCE PARAMETERS

RECEIVING PROPERTY - It does not have the long wire antenna so that as many islands as possible must be included in the diode strin .

RESISTANCE PROPERTY - The islands must be sufficient close to ensure the direct tunneling mechanism, and sufficiently far away to give sufficient diode resistance for optimum flat top operation.

DIODE CIRCUIT OPTIMIZATION - The diode may have to be loaded and biased for best detection response for a particular inter-island spacing and particular metal islands.

V-BAND DETECTION AND MIXING

Follwoing our success at X band, we happened to have V band equipments available and felt we could provide a broader bandwidth test for the MOM diode of up to as much as near 10 GHz.

In the process of familiarization with these equipments, we performed the detection experiments first. These were Impatt diode sources with a 7 GHz tunability and no internal modulation. A ferrite switch was thus incorporated in the microwave plumbing to act as a modulator (see schematic in Fig. 8).

At this stage we had decided that unless we achieved some measure of stability of the diode, we could not perform the mixing tests. This was a necessary condition since with such bandwidth (7-10 GHz) in mind and no spectrum analyzer of this bandwidth available, it would be virtually impossible to find the beat of two V band sources and an X band source (three frequency beating) and display it on the narrowband scope amidst the noise generated by instabilities.

Full scale etching studies were launched at this point to correlate the slender ratio with diode detection performance. Our efforts are graphically demonstrated in Figs. 9-13. It is quite evident that as slender ratio value increases, so does stability of the diode with no significant sacrifice in responsivity. Short term stability over hours was achieved with repeatability.

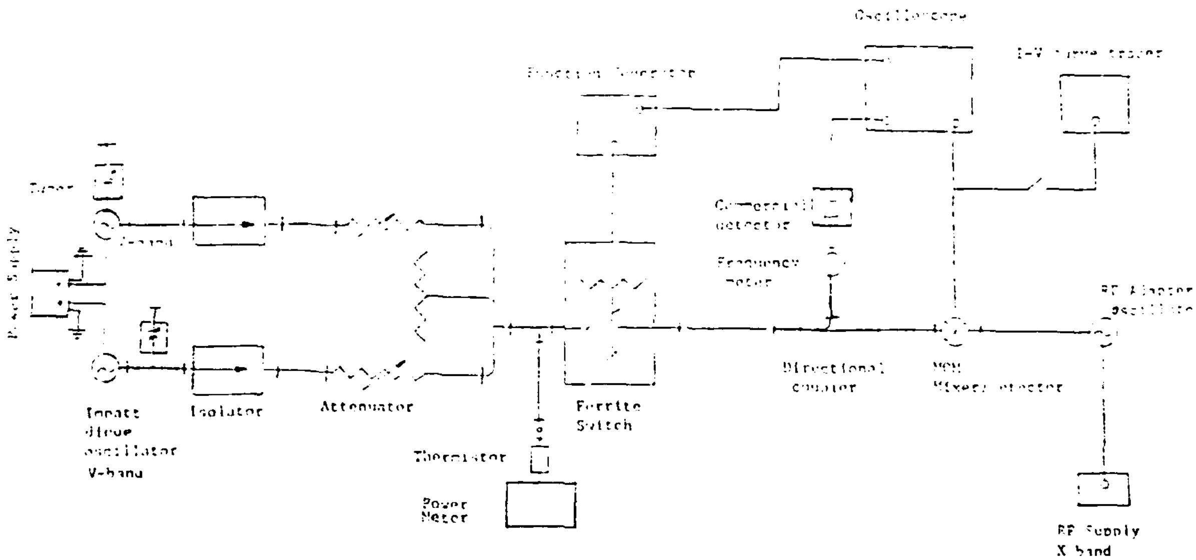
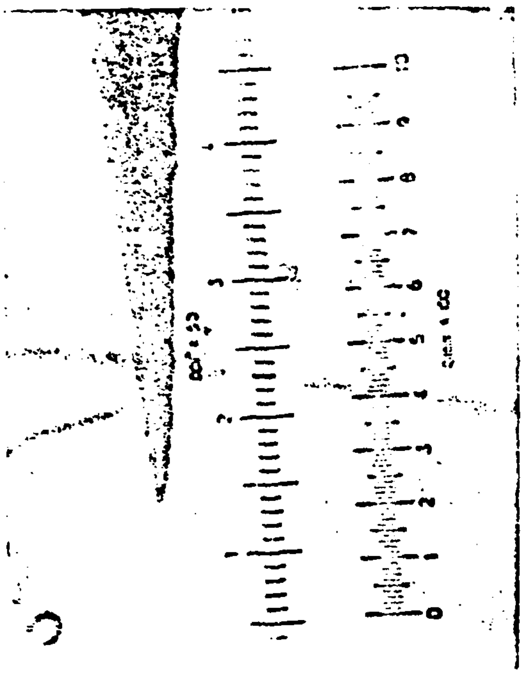


Fig. 8 . Experimental set-up: V-band radiation detection and mixing.

Whisker 1



Before Test

After Test

Comment: The point is blunt, with a small slender Ratio. The response was 0.2mv volts peak to peak and unstable. No hook was formed.

Fig. 9

Whisker 2

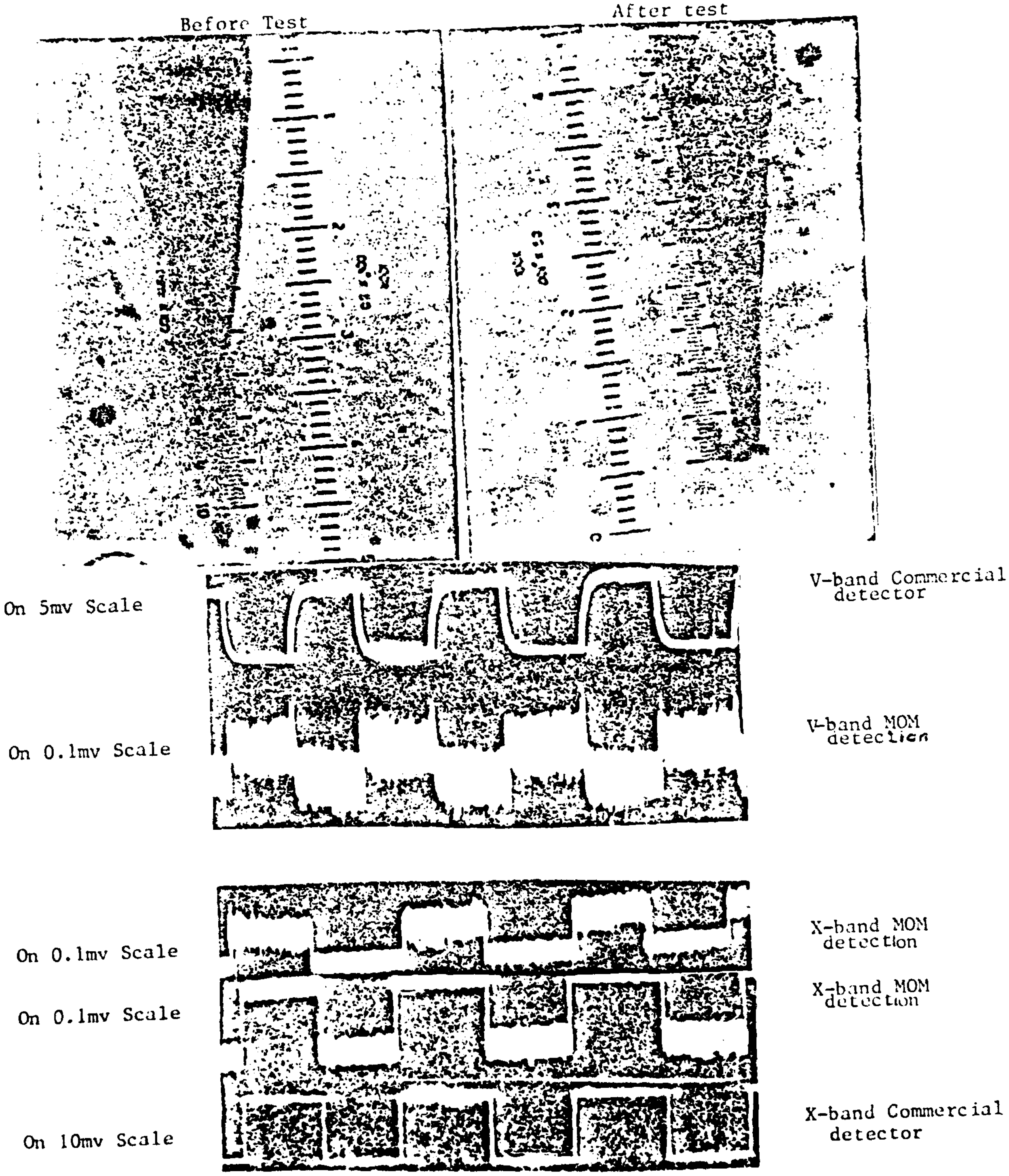
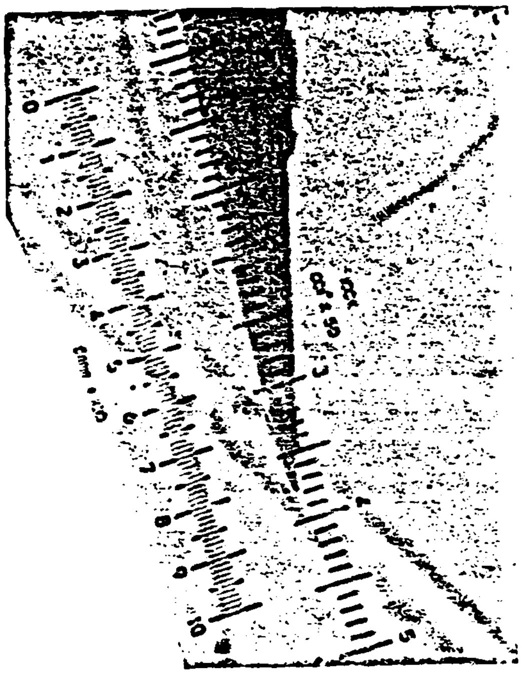


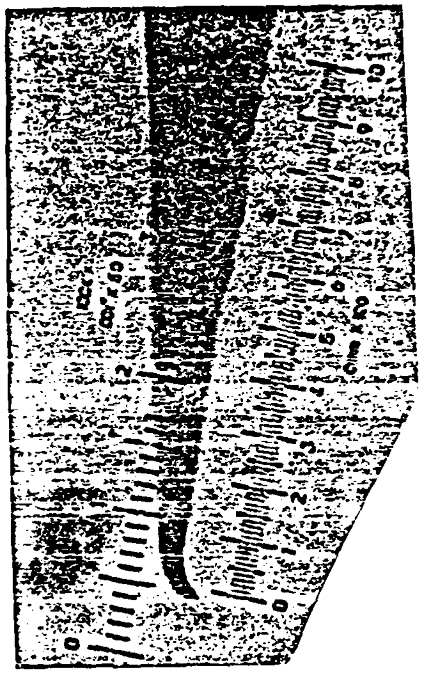
Fig. 10

Whisker 3

Before Test

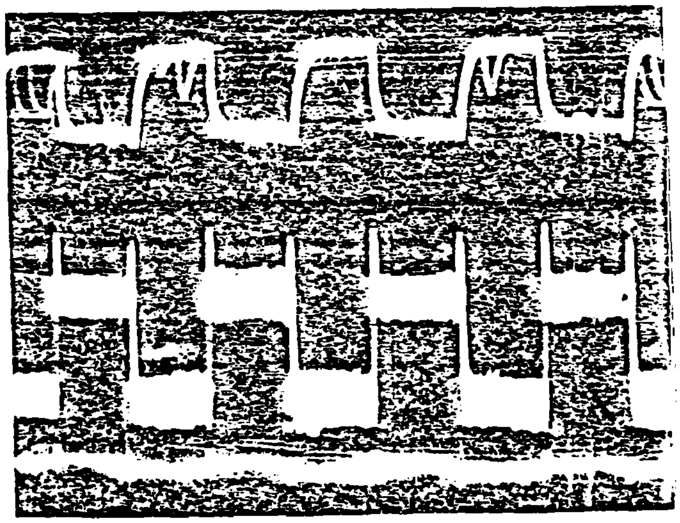


After Test



On 2mv Scale

Commercial V-band detector



On 0.5mv Scale

MOM-Detector

ferrite Switch driver voltage

Comment: The spikes on the MOM-detector response result from channel feed-though of the ferrite Switch driver Voltage (20v). Response was quite stable.

Fig. 11

Response

After Test

On 1mv scale

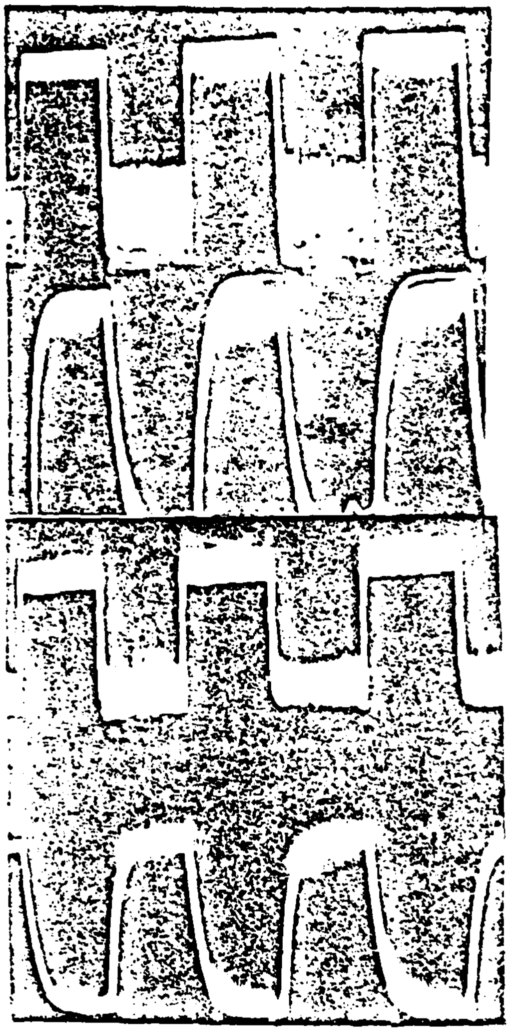
instability

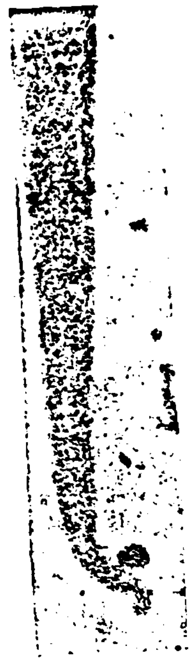
On 2mv scale

On 0.2mv scale

instability

On 1.0mv Scale
Commercial
V-band detector



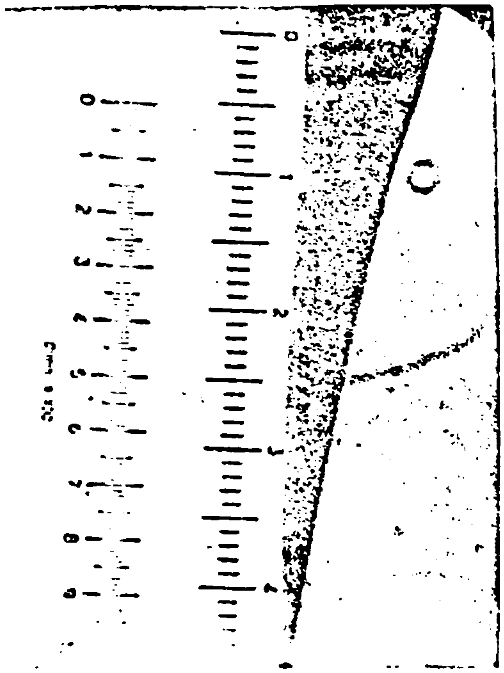


Comment: The response on 2mv Scale is taken with reduced contact pressure. Response is high and reasonably stable.

Fig. 12

Whisker 5

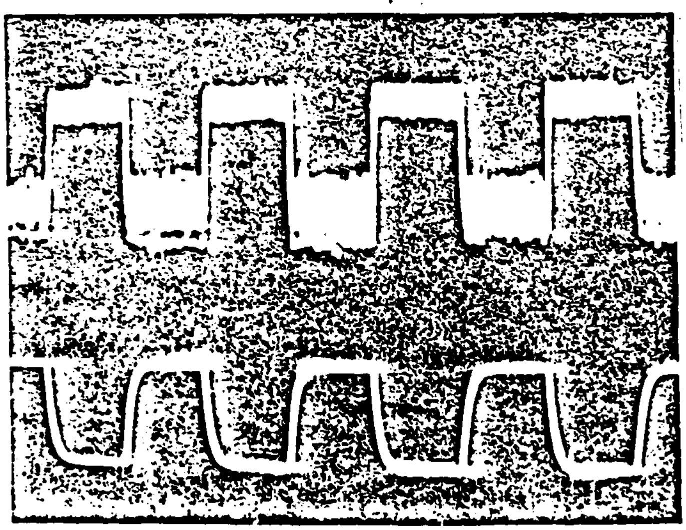
Before Test



After Test

On 0.5mv scale

MOM-Detector



On 1.0mv scale

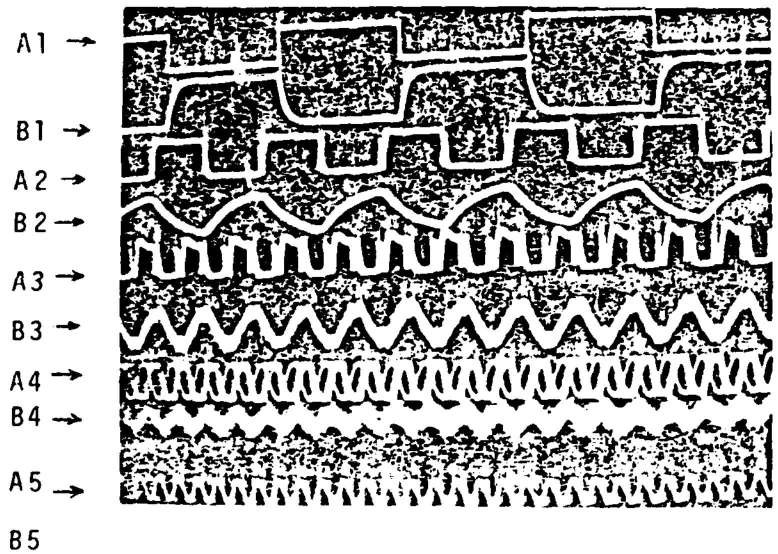
V-band Commercial detector.

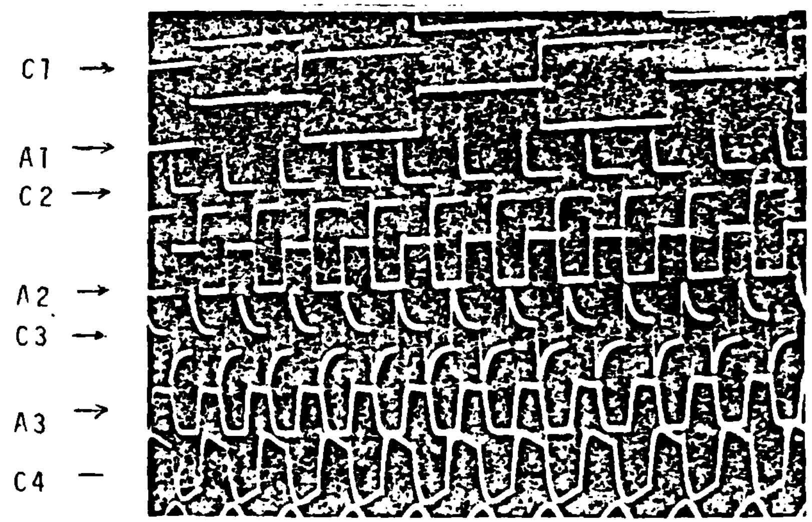
Fig. 13

As an after thought, the MOM diode was compared with the commercial V band diode for frequency response by varying the switching frequency. Vivid demonstration of the superiority of the MOM diode appears in Figs. 14, 15. A note of caution is that the MOM diode is in an open structure, while the commercial diode is packaged so that its frequency cutoff may be due to packaging parasitics rather than parasitics of the diode itself.

The commercial diode also did not respond in the waveform of the switching voltage, while its spiking was easily picked up by the MOM diode.

As the necessary next step, the diode was tested for long term stability. Since only one diode mount was available, the diode was tested for a maximum of 21 days with the results shown in Fig. 16. In this test, the diode mount was enclosed to keep out draughts in the room, and no adjustments were made during the entire period. After this period, for curiosity contact pressure was reduced as the tip was pulled away from the post and the diode response and stability observed. Response increased somewhat, but deterioration in stability was evident.





A - MOM detector response; B - Commercial detector response; C - Switching voltage waveform

Scale: A1, B1 - 1 mv; A2, B2 - 1 mv; A3 - 1 mv, B3 - 0.2 mv; A4 - 1 mv, B4 - 0.1 mv; A5 - 1 mv, B5 - not observable on 0.1 mv scale.

Switching frequency: 1 - 100 Hz; 2 - 1000 Hz; 3 - 4 KHz; 4 - 20 KHz; 5 - 50 KHz

Fig. 14. Detected voltage amplitude and waveform versus switching frequency

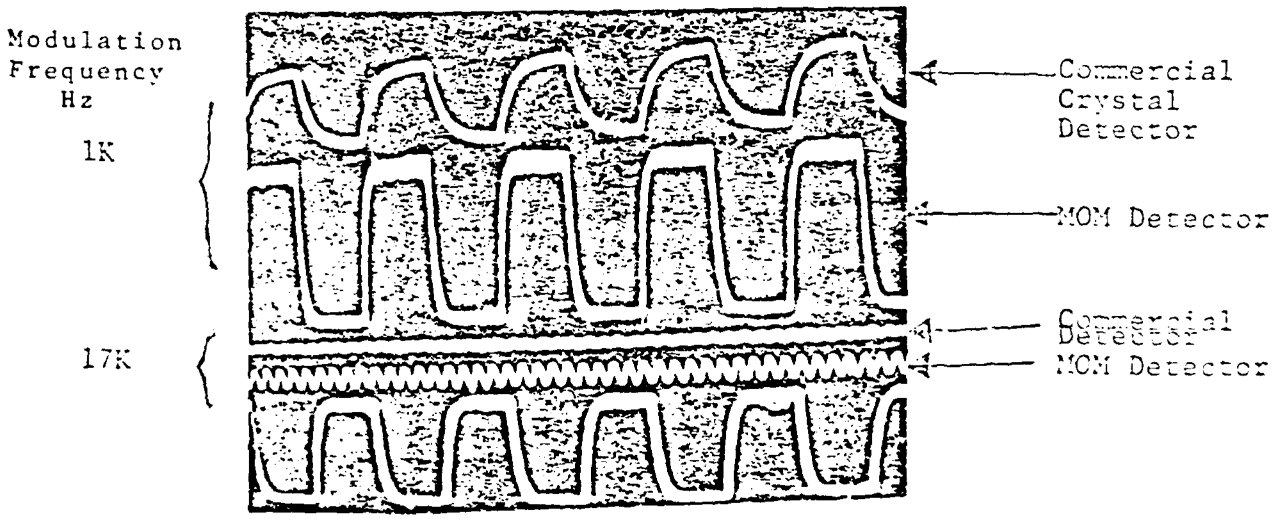


Fig. 15. Increased switching frequency resulted in a reduced detected signal or both the commercial and the MOM detector.

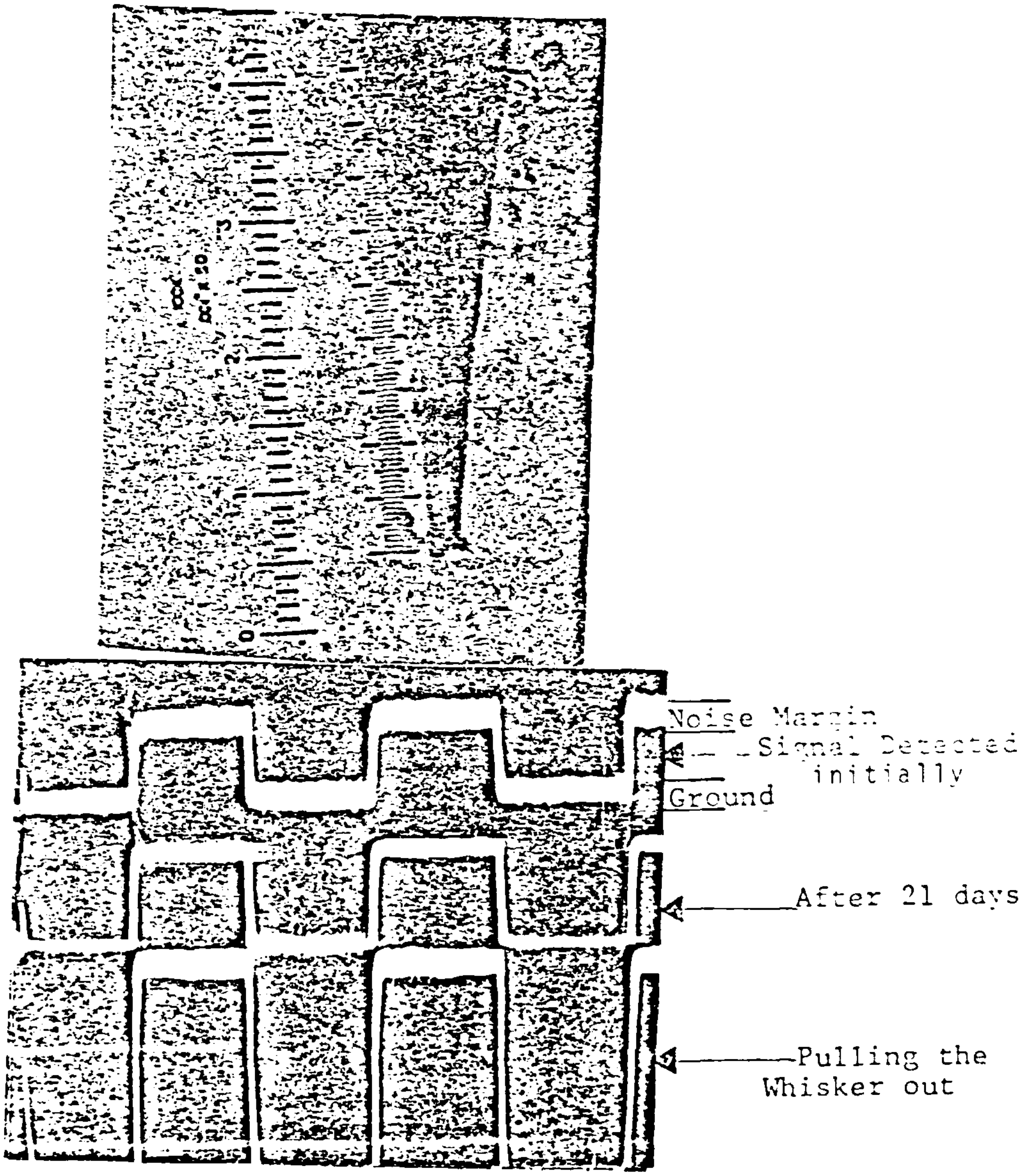


Fig. 16 . Longterm stability study, detection lasted for weeks. Notice that the signal is noise free.

Only when stability of the diode was achieved did we go ahead with the mixing experiment. The two V band sources were pulled apart in frequency to about 7 GHz, a value that could be readily beat with the tunable X band source. The X band was modulated for better indication on the scope, while the Impatt sources ran CW. Since V band frequency meter was available, it was not difficult to set the frequencies of the V band sources and their difference calculated. The X band source was then tuned to this difference frequency with the final beat shown very well on the scope. Since the scope was narrowband, roll off of the beat was quite rapid. Two versions of the beat signal with two different whiskers are shown in Figs. 17, 18.

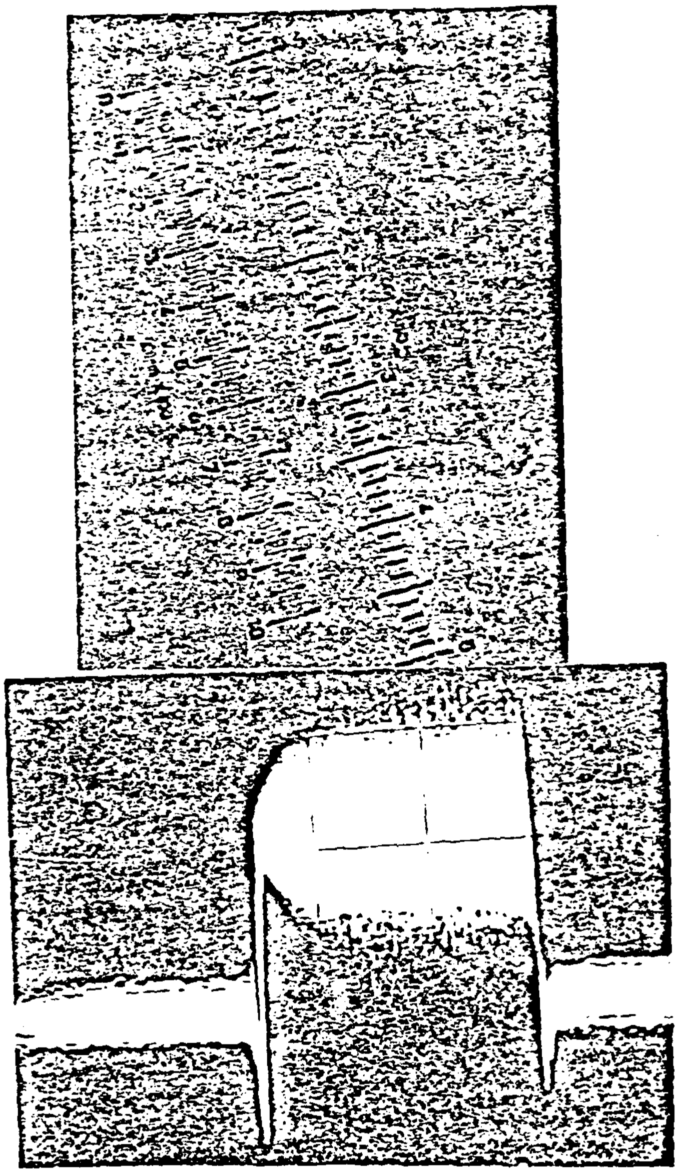


Fig. 17. Result of beating two V-band 7GHz apart with a tunable 10GHz RF source.

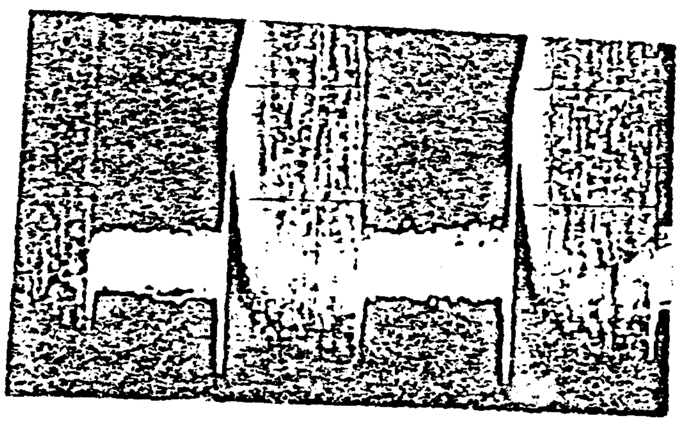


Fig. 18. 'hisker with a different slender ratio produced a slightly different mixing response.

DYNAMICS OF CONTACTING OR HOOKING OF WHISKER TIP

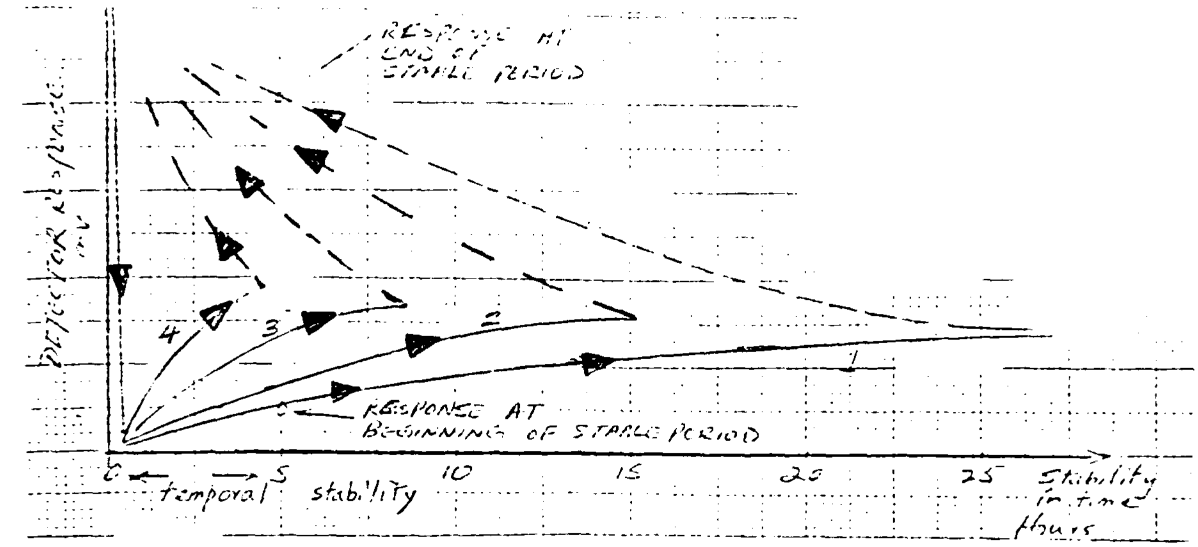
There are so far two ways of contacting or hooking the tip with the proper slender ratio. We believe one way will lead to better stability for the diode than the other. The dynamics of both contact methods is shown in Fig. 19.

Since we believed that sufficient contact pressure had to be brought about at the whisker tip before a hook would form, in contacting method 1, the tip was advanced towards the nickel post until an electrical short was registered. This was our indication of the formation of a hook, and the tip was retracted gradually. The retraction steps were such that at every step the tip was left untouched for a period to see whether stability could be established. The response would be low, but stability high as shown by curve 1 in Fig. 19a. In order to improve response, further retraction of the tip was made until another point of stability was reached as in curve 2. The condition represented by curve 4 was highly unstable, but with corresponding high response. Our efforts were then to maximize the response-stability triangle area. However, an additional controlling parameter must be considered and this is the initial tilt of the triangle, which is totally a function of the slender ratio. Thus, in Fig. 19b, the whisker with slender ratio 2 is better than that with slender ratio 1.

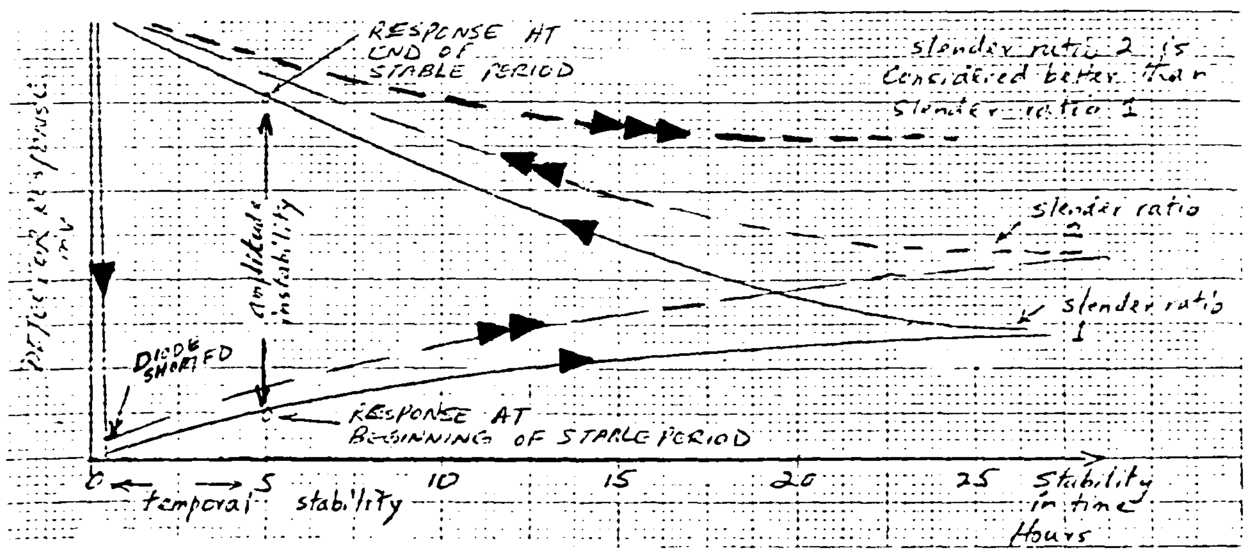
We finally realized that in this procedure contact pressure of the tip was maintained by the hook itself through its own relaxation, which was highly unpredictable. This stability condition became increasingly sensitive to the decreasing contact pressure,

which was increasingly unpredictable. We are thus always faced with a compromise situation between stability and responsivity. However, we do know that the hooked structure can provide a remarkable degree of mechancial stability for the point contact diode as long as the stress at the contact point is maintained.

Contacting method 2 was implemented precisely to achieve this goal - maintenance of constant contact pressure. This procedure consisted simply of reversing the contacting method 1. Thus, the sharp whisker tip was brought in contact with the nickel post with great caution. Contact pressure was increased very slowly, and its V band detection monitored. Once a detected signal of sufficient amplitude and stability was observed, the tip was left in that position under presumably constant stress. This procedure was applied to a number of tips with different slender ratio with convincing indication that we are moving in the correct direction. Typical result is shown in Fig. 19 b (the ▷►► curve).



a



b

Contacting method 1

Contacting method 2

Fig. 19. Diode response versus temporal stability curves

HEATING STABILITY

V-band detection was first established and stablized with the formation of the hooked tip. The MOM diode was left undisturbed over a period of a few days so as to ensure stability. The approximately aligned CO_2 laser beam with respect to the MOM junction area was then focused. The MOM point mounted on an xyz-θ translation stage was then moved into the focal region of the laser beam. The laser beam was chopped so that it could be detected on the MOM diode. Observed detection of the infrared radiation demonstrated the capability of the MOM diode as an infrared detector, and also pinpointed the spot of incidence of the laser radiation. Maximum detected signal indicated the exact hit of laser radiation on the junction area. The chopper was then removed and V-band detection resumed. The V-band signal with and without CO_2 laser heating was recorded. The laser beam was also chopped at different speeds so as to vary the amount of heating. Detected signal did not vary more than two-fold in the entire heating range with CO_2 laser power peak at 6 watts. Some of the results are given in Fig. 20.

Heating by the laser beam was quite considerable since in one instance portion of the tungsten whisker was evaporated. It appeared to us at this stage that the hooked tip feature of the MOM point contact diode could successfully remove the major instabilities of mechanical vibration and incident radiation heating. The latter is inherent in all other alternate MOM structures such as sharp tip with a loop and thin film structures.

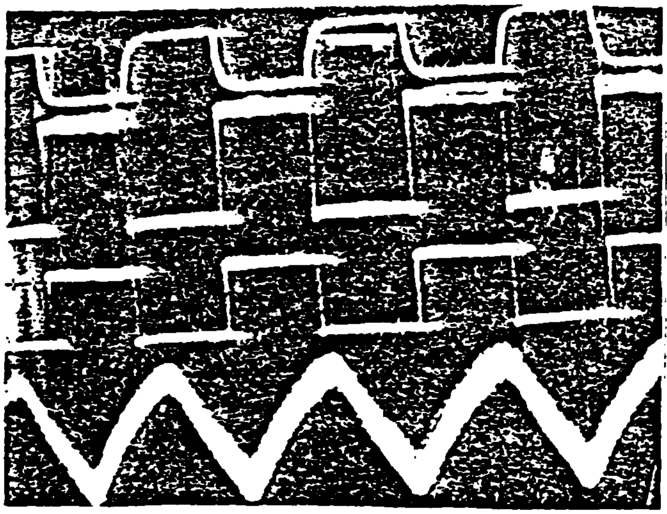


Fig. 20. V band detection under laser heating

INFRARED DETECTION AND STABILITY

In parallel with the V band experiments, the MOM point contact diode was also tested for detection of 10.6 micron CO_2 laser radiation. The open structure of the diode mount provided easy access of any type of radiation to the diode simultaneously. The laser radiation was focused onto the diode junction area with a Ge lens after the beam was chopped for modulation. Focusing was necessary both for concentrating laser power at the junction area and localizing the radiation so as not to overheat other portions of the diode. Laser line mixing was not attempted in this series of experiments due to lack of equipments such as another frequency stabilized laser with fine tuning, and other auxiliary equipments such as mm wave harmonic chains to provide a harmonic suitable for beating with the laser difference frequency that could be displayed on commercial spectrum analyzers. This series of experiments were aimed at stability studies in infrared detection with the assumption that stability results were applicable to mixing.

The first detection experiments were with unhooked tips, and the observed results are shown in Fig. 21. As expected, the response was high but extremely sporadic, and did not correlate with the chopping frequency. Spiking continued in a regular fashion even when the chopper was removed, indicating that laser heating of the tip was taking place, which caused expansion of the tip into the oxide layer until it came in contact with the nickel post. The latter then acted as a heat sink, cooling the tip, which contracted until contact was broken. The tip was reheated by the laser radiation and the above process repeated once more, resulting

in the appearance of a pulse train, although the chopper was removed.

No such spiking was observed once a hook was formed. Generally, the detected signal followed the chopping frequency, indicating the heating effect was essentially removed. The signal waveform varied somewhat, depending on the whisker slender ratio. Thus, too large a slender ratio, i.e., very slender whiskers, leads to excessive hooking and a response with a slower rise time. Typical hooks and their responses are shown in Figs. 23-25.

To further assess heating effect, the chopping frequency was varied from a few Hz to 2000 Hz. Accoridng to the results shown in Fig. 24, the amplitude of the response remained approximately constant, indicating that the waveforms displayed were not due to heating and cooling cycles of the tip as concluded in the case of sharp, unhooked tips.

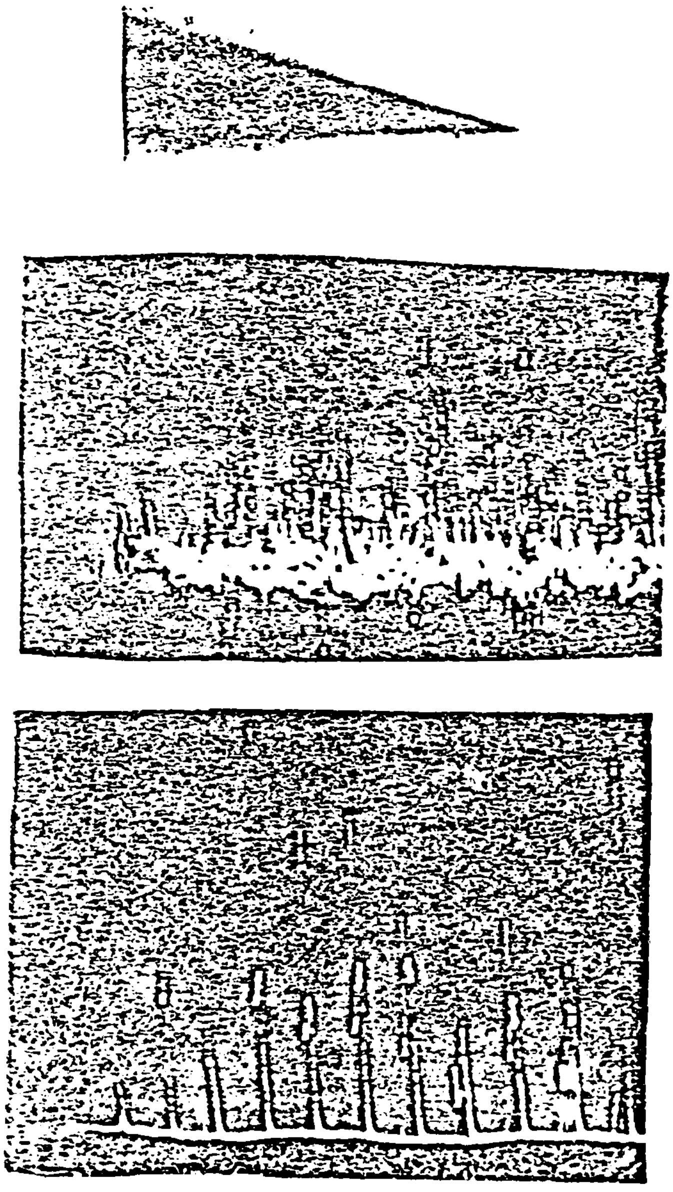


Fig. 21. Response of a short, sharp whisker.

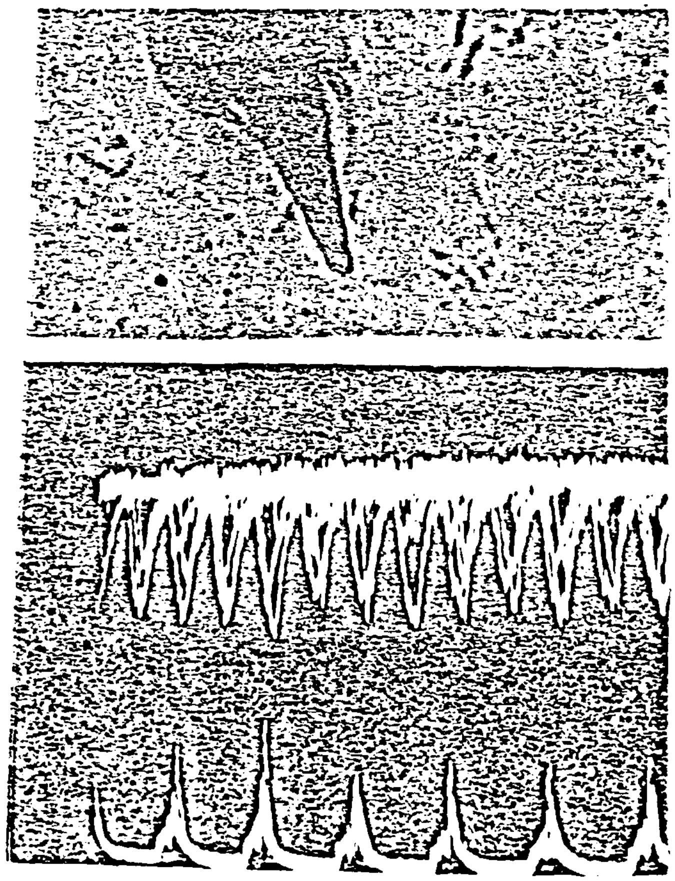


Fig. 22. Response due to a blunt unhooked tip.

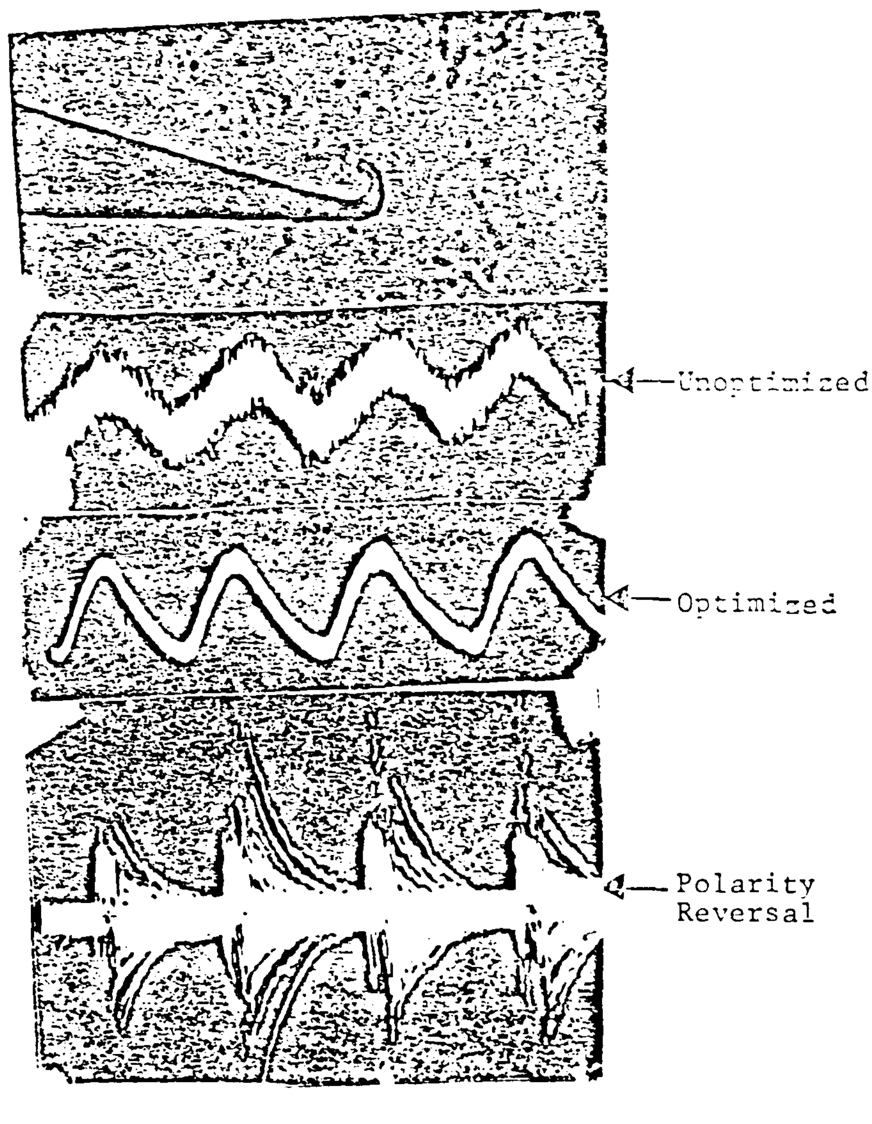


Fig. 23. Large hook produced a saw-tooth detection. Polarity reversal was noticed only when the contact pressure was reduced.

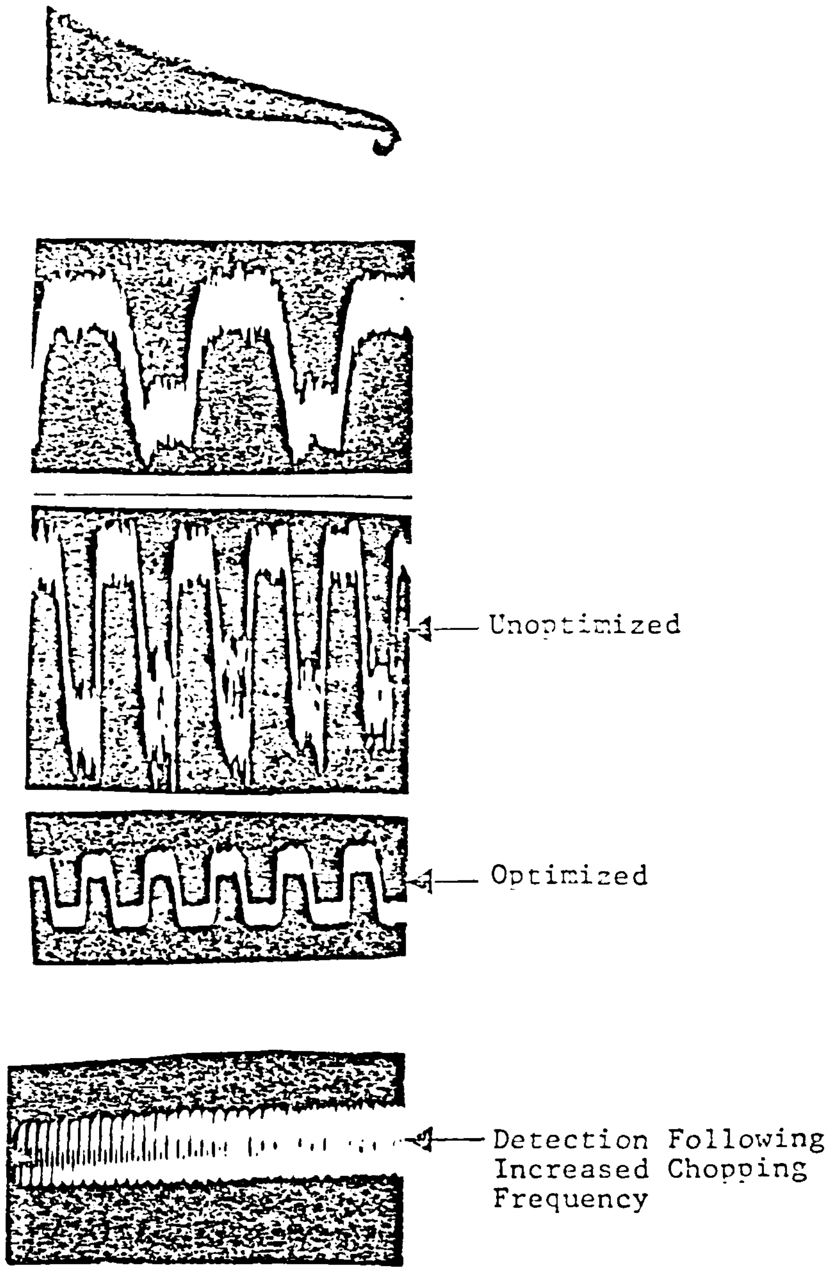


Fig. 24. Nicely formed hook with a good slender ratio. Notice that detection follows chopper frequency.

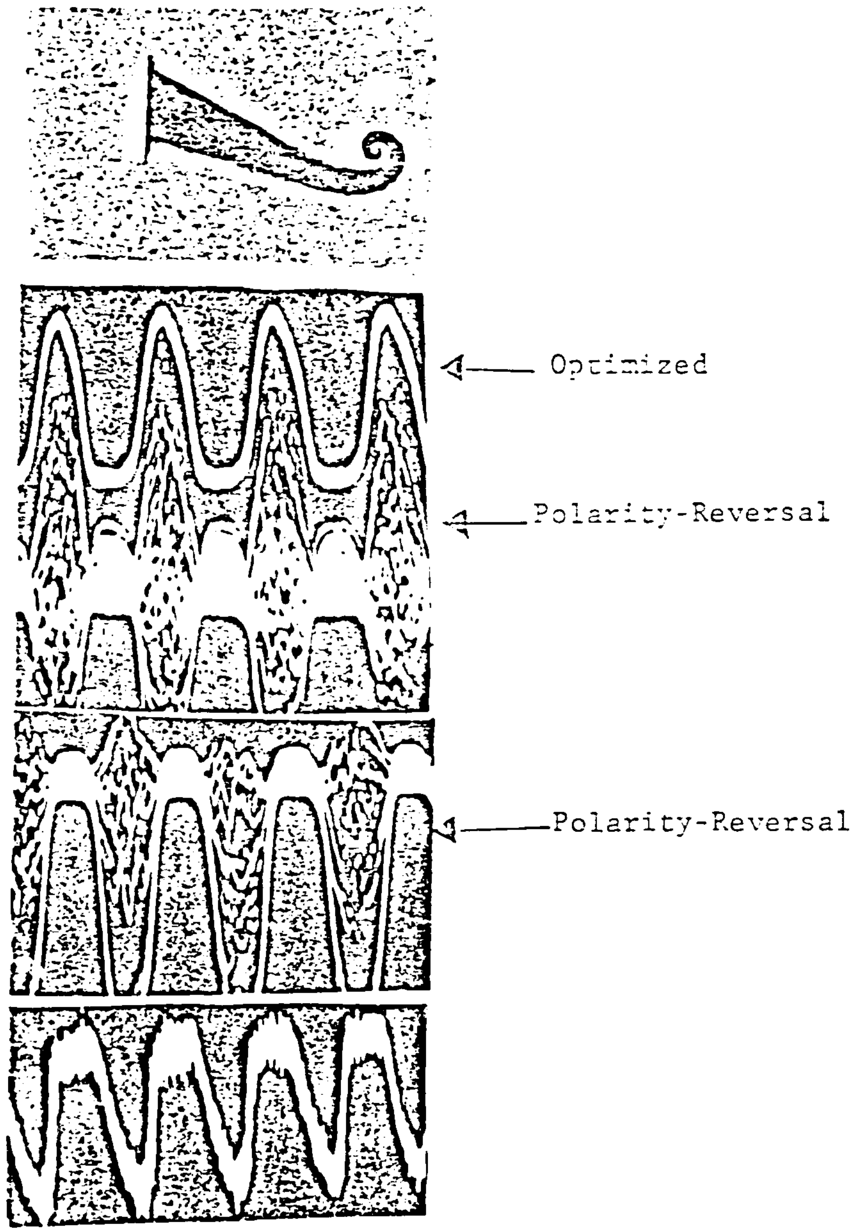


Fig. 25. An excessively hooked tip.

ANOTHER COHERENT DETECTION SCHEME IN THE V BAND

In an attempt to improve diode characterization by system testing of the point contact MOM diode, we have gone to the coherent detection scheme, in which a very weak x band signal is pumped by the beat of the two V band oscillators in the MOM diode. The coherent detection scheme is shown. As the data presented indicate, such a scheme can detect extremely weak signals even when the MOM point is highly unstable. In passing, we note that the x band signal frequencies are 8.26 and 10.9 GHz, thus demonstrating the extreme broadband nature of the MOM diode. However, MOM point stability is most important in the case of direct or incoherent detection, where no amplifying effect exists by means of local oscillators. Since most researchers use the MOM point contact diode for heterodyning or coherent detection, they have not paid much attention to diode stability. We are interested in both detection schemes and stability should be considered as an important diode parameter.

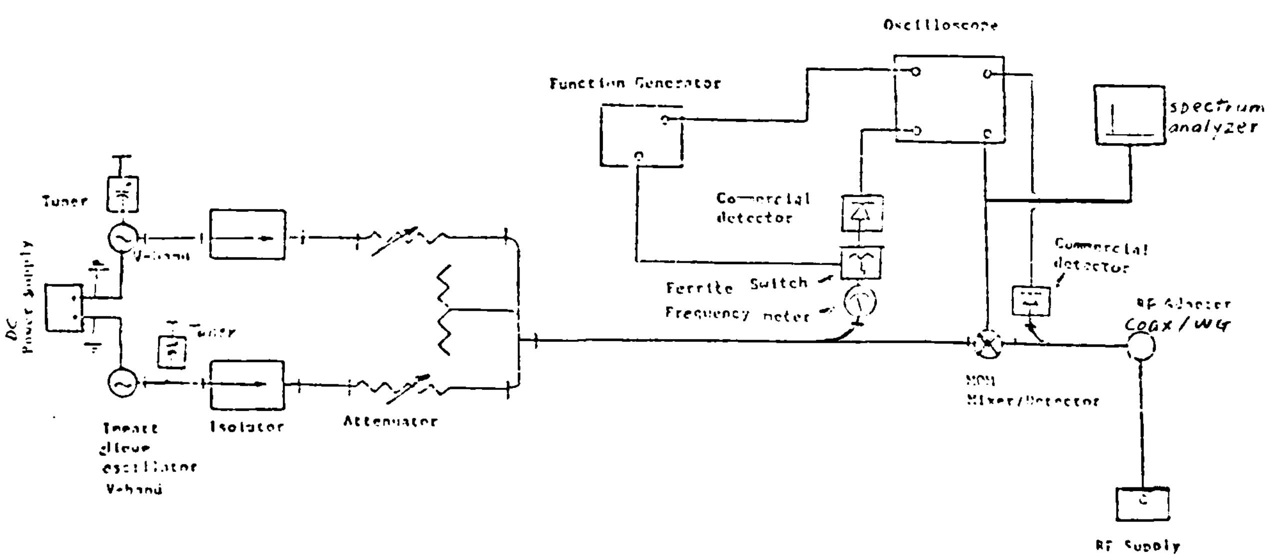
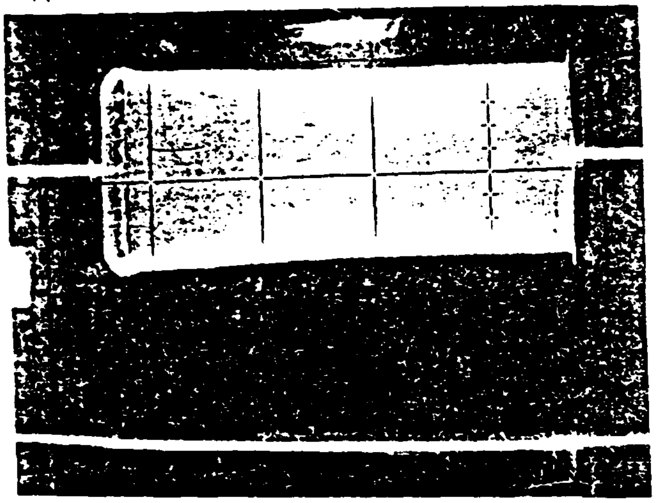


Fig. 26
2 V band local oscillators providing a beat in the X band

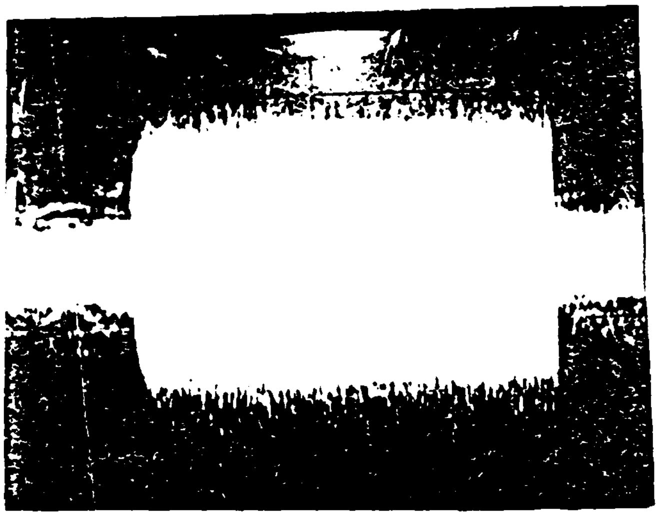
signal



X band signal is directly detected (incoherent detection) (a) and coherently detected and amplified by the beat between the two X band oscillators

Beat frequency is 8.25 GHz

MOM point contact diode is stable



X band signal at 10.9 GHz coherently detected

MOM point contact diode very unstable

Fig. 27

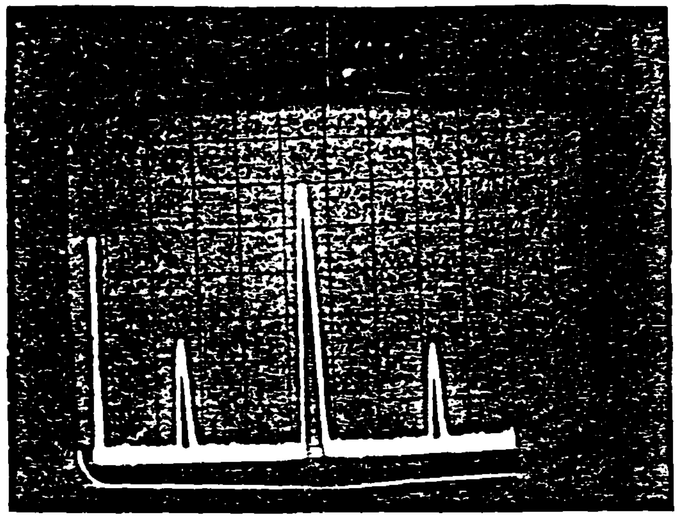


Fig. 28. MOM point contact diode output A using coherent detection scheme

DISCONTINUOUS METAL FILM - X, V BAND DETECTION AND MIXING EXPERIMENTS

We have begun a systematic testing of the discontinuous film MOM diodes. Blunt tip and gold-ball tip probes are used as electrical contact in an attempt to eliminate nonlinearity of the I-V characterisitc due to sharp tip effects. X band detection was first attempted to acquaint ourselves with the detection chracteristics of these films. X band mixing experiments then followed to ensure that the signal obtained is genuine signal from the MOM diode. V band detection was then performed. Experiments are still in progress on V band detection and mixing tests of various types of films and geometries.

The data obtained so far are shown in the figures and tabulated. The general conclusions reached are as follows: Pd-Au combination films are superior in performance to Pd films due possibly to the difference in work functions of the dissimilar metals; the films deposited have too low a film resistance, meaning that the islands are too close together, leading to great difficulty in tapping the rectified voltage from the film. Film resistance is artificically raised by deliberately making poor contacts between the probes and the film, and this leads to instability of the signal, a feature we would like to eliminate with thin films deposited on glass substrates.

Figure 29.1 was obtained with freshly deposited Pd-Au combination film. The detected x band signal is quite stable over a short time. and was dependent on the contact resistance of the diode. Thus the signal was enhanced substantially by raising diode resistance through the probe tips from 170 ohm to 1 K ohm (Fig. 29.2).

Figure 29.3 gives the result of x band detection on Pd-only film. Film resistance is higher due to absence of gold, and the detected signal was lower as anticipated due to the similarity of the metal islands.

In an attempt to improve stability, we change one of the probes to a gold ball tip (the other probe remains to be a blunt tip). There was substantial reduction in the sensitivity of diode resistance to contact pressure between probe and film. X band mixing was achieved and shown in Fig. 29.4 V band detection was attempted to no avail.

We therefore tried V band detection with the higher performance Pd-Au film, and were able to observe detection. The results are shown in Fig. 29.5 Strangely, the diode resistance in this case was 100K ohm. This led us to conclude that the film was probably not uniform, and there are strips where the film resistance is very high.

To verify this, we returned to the Pd strips we prepared previously, which gave rather high film resistance. X band detection was achieved and shown in Fig.29.6 Film strip resistance reached 150 K ohm with two gold ball tip probes.

We have therefore concluded that we must proceed to film strips with dimensions of mm to extract usable metal island groups, which will provide good tunneling conduction and high diode resistance. Ideal diodes should have resistance of the order of 50K to 100K ohm. Good tunneling involves small island separation and large work function difference, the former tend to lower diode resistance. Thus, Ni films are being considered since nickel forms oxide naturally with extremely high resistance (of the order of 10^{15} ohm-cm). Hence, Ni islands can be very closely situated and the resulting film can still have rather high resistance. However, deposition of nickel must be done in high vacuum, which poses rather severe technological problem. We feel, nevertheless, a vacuum of 10^{-6} Torr may be adequate due to the briefness of the deposition process.

Our point contact diode work is still progressing and has helped us greatly in understanding the nature of the disontinuous films. Thus, the optimum oxide film thickness for rectification established for the point contact diode provides the guideline for the deposition of thin films. Hence there is an optimum separation of islands for best diode response, especially in the case of dissimilar metals both because of the dependence of tunneling on metal separation and dependence of diode resistance on oxide layer thickness and resistance.

Picture #	Curve #	Diode type	Film type	Operation	Probes used	Voltage scale	Current scale	R
1	a'	commercial		x band detection		0.1v/div		
	a	MOM film 1	3:1 Pd:Au	"	2 blunt-tip probes	0.5mV		
1'		MOM film 1	"	I-V curve	"	0.05V	0.2 mA	170 Ω
2	a	"	"	x band detection	"	1 mV		
2'		"	"	I-V curve	"	0.05V	0.2 mA	1 KΩ
3	a	MOM film 2	Pd only	x band detection	"	0.1 mV		
	b	"	"	"	"	"		
3'	a	"	"	I-V curve	"	0.2 V	0.1 mA	2KΩ
	b	"	"	"	"	"	"	6KΩ
4	a	"	"	x band mixing	1 blunt tip & 1 gold ball tip	0.2 mV		
	b	"	"	x band detection	"	"		
5	a'	commercial		X band detection	2 blunt tip probes	1 mV		
	a	MOM film 1	Pd:Au 3:1	"	"	0.5 mV		
5'		"	"	I-V curve	"	0.05V	5 μA	100KΩ
6	a	MOM film 3	Pd strip (old film) 3mm × 2mm	x band detection	2 gold ball tips	0.1 mV		
	a'	commercial		x band detection		0.1 mV		
6'		MOM film 3	Pd strip	I-V curve	2 gold ball tips	0.1 V	5 μA	150KΩ

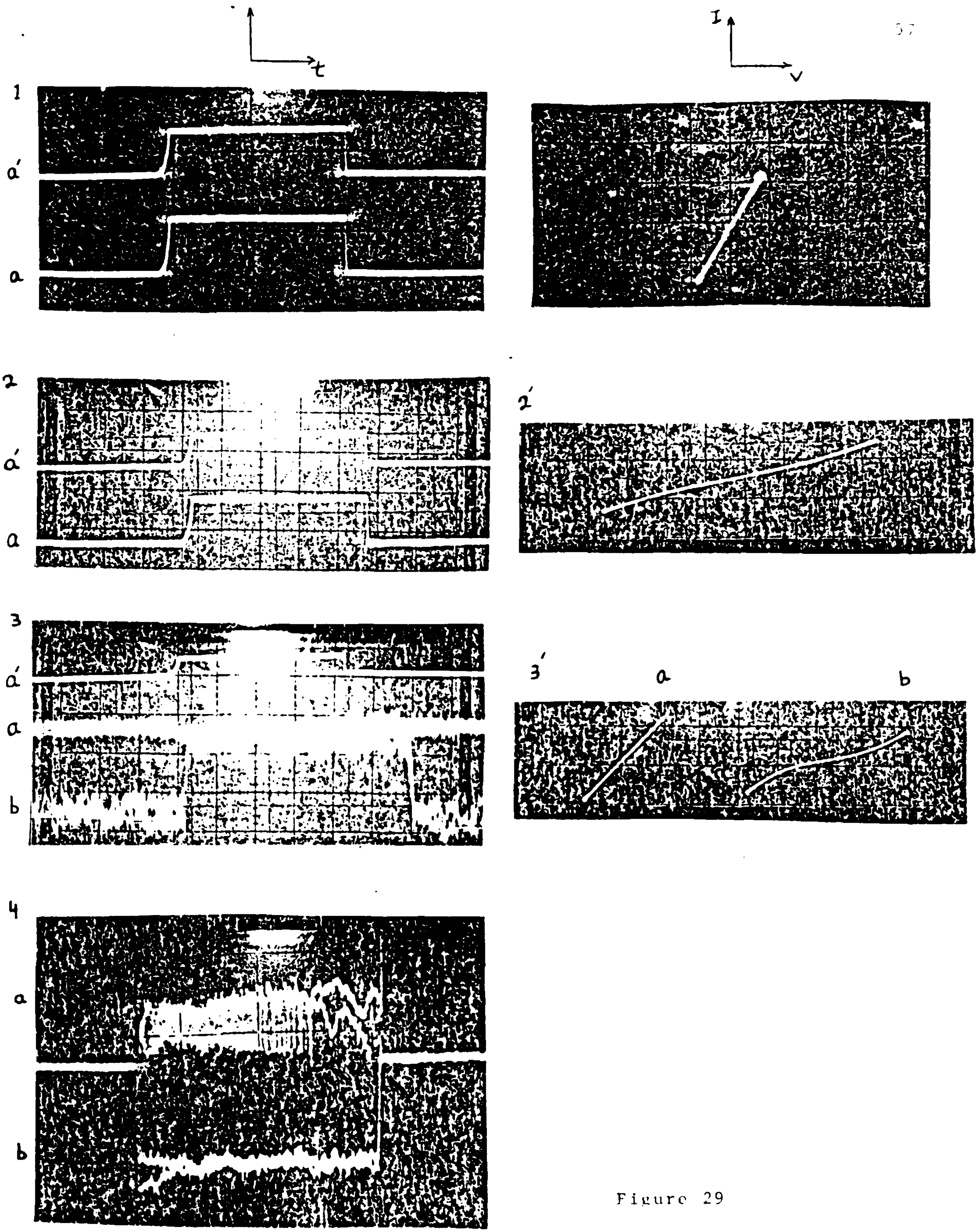
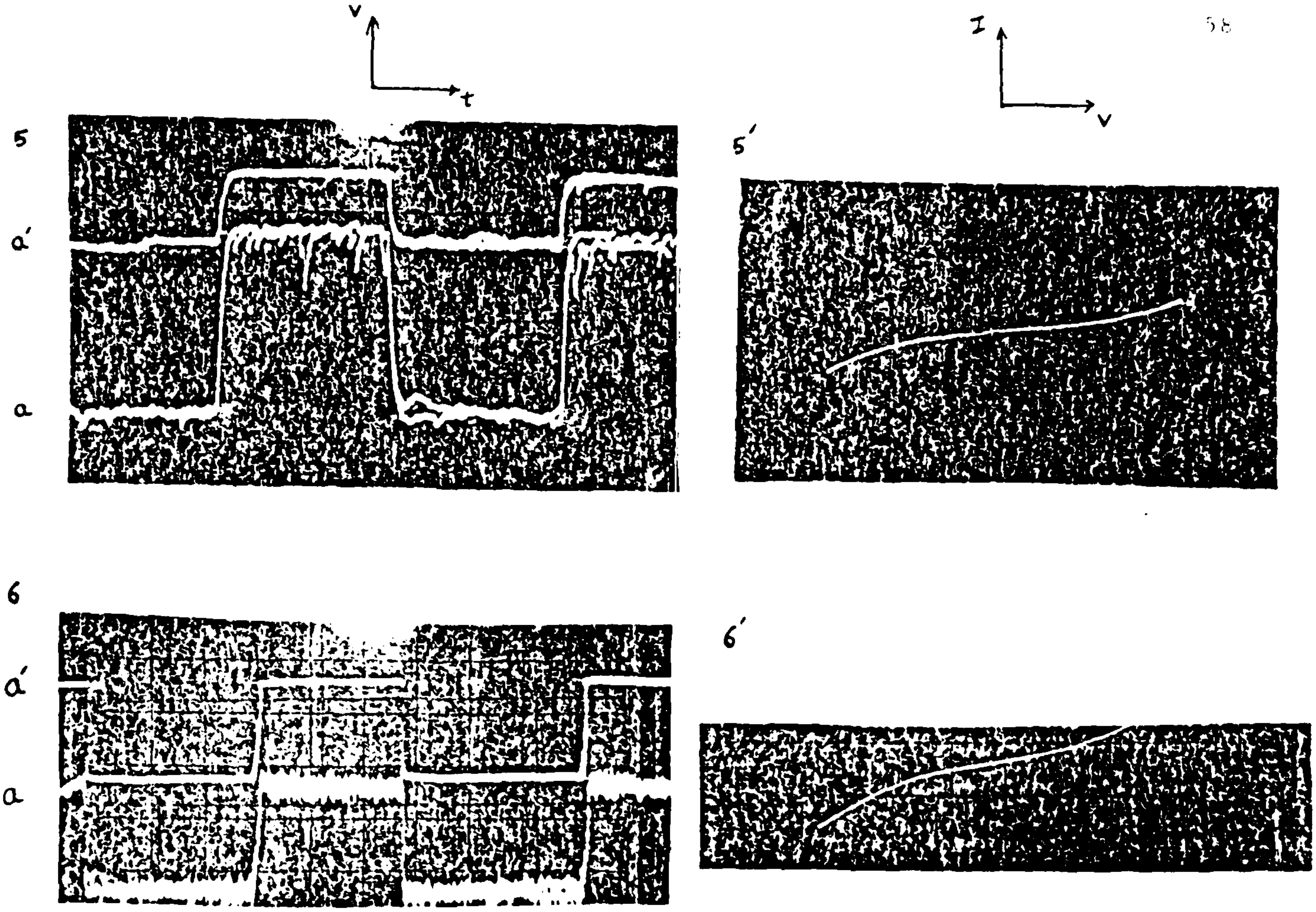


Figure 29


V
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I
V
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6
a'
a
6'

The discontinuous MIM films we have prepared so far demonstrate clearly the feasibility of achieving detection and mixing up to V band. The inability of the films to produce signals comparable to the point contact MOM diode is essentially the result of the lack of the long wire antenna and the significantly lower resistance of the film. Two avenues are being pursued to alleviate this problem. Working on the definition that a "good" island grouping is one that has optimum island spacing for the preservation of the tunneling process while producing a substantial overall diode resistance of the order of kiloohms, we can either improve the film itself by varying the film deposition rate or search for best island grouping by making film strips of the order of the aperture of the waveguide.

Film strips have been prepared and tested up to now with widths of 1 mm or less and varying lengths. Gold ball tips are used as contacts for tapping the signal. Contact pressure is no longer a stability factor. These probes still allow us to probe the strips for bets resistance paths. The detected signal once realized is stable. To enhance detectability, X band oscillator power is raised to 300 mW (as compared to 10 mW previously). Stable detection at X band is observed and shown in Fig.30 for Pd-only films with a film strip resistance of 2.5 K ohm. This low signal is significantly enhanced with slight lateral movement of the probes, as demonstrated in Fig.31. This is exactly the situation in which a better island path has been established, while film strip resistance remain constant. The Pd-Au film combination strips are then tested with considerably more stable signal detection at a much lower film strip resistance of 100 ohm (Fig.32). This is a clear indication of the superior detectability of the combination film, since if film resistance were of the same order of that of the Pd-only films, the output signal would have been much higher. Furthermore, so far the Pd-Au film is the only one that will detect V band radiation with the same measure of stability. No stable detection is observed with Pd-only films (Fig. 33).

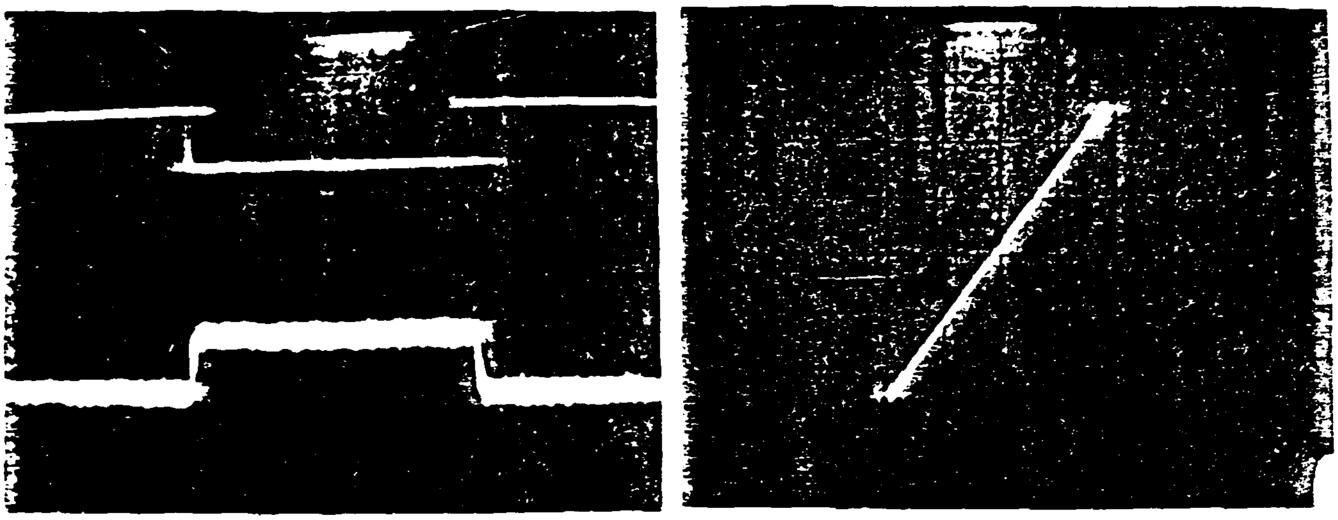

Fig. 30
Pd-only film strip - X ... detection: a- commercial detector;
b- MIM film strip (0.1 mV/div)
c- I-V curve for film strip
R = 2.5 KΩ.

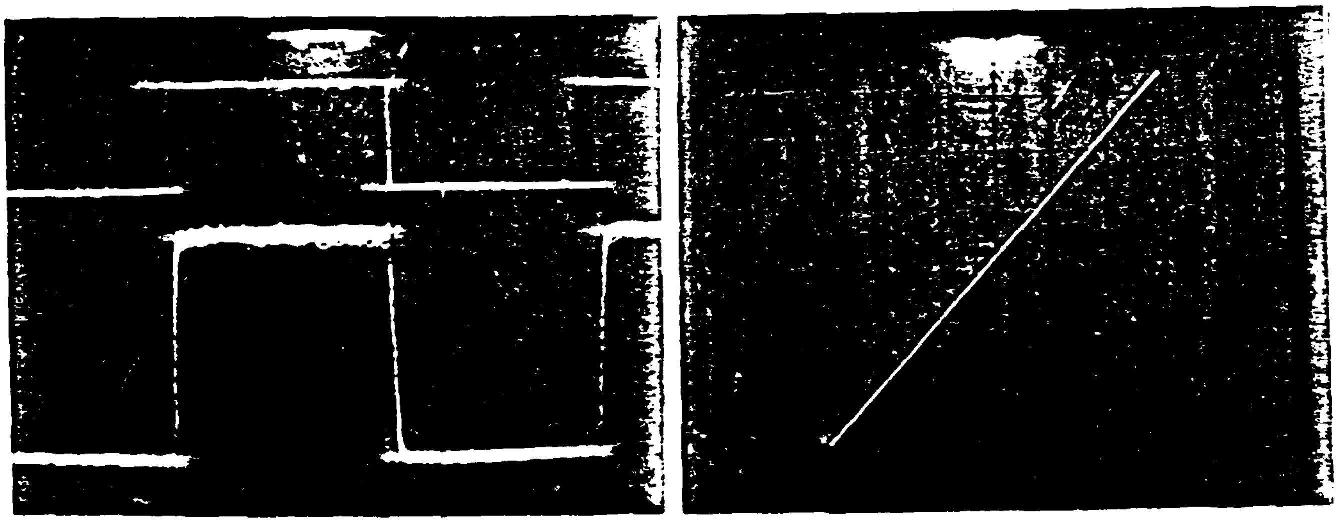

Fig. 31 [illegible] film [illegible] ial [illegible]

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PRELIMINARY PROGRAM

1981 IEEE INTERNATIONAL CONFERENCE ON INFRARED AND MILLIMETER WAVES

The Carillon Hotel
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C. Yu, M. Ndeti and S. A. Byers, Department of Electrical Engineering North Carolina A&T State University, Greensboro North Carolina 27411

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OPTIMUM SLENDER RATIO FOR MECHANICALLY AND THERMALLY STABLE HIGH POWER MOM POINT CONTACT INFRARED DETECTOR*

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Abstract

Thermally and mechanically stable and durable MOM point contact infrared detectors up to multiwatt range is achieved by an optimum "Slender Ratio" for hook formation which has so far not been analyzed theoretically.

Introduction

The Metal Oxide (MOM) point contact diode has been used extensively over the past three decades for frequency measurements in the infrared.[1,2] Recently, this diode has been used for detection and measurement of frequency differences between visible laser lines of up to 170 GHz.[3,4]

In spite of their excellent characteristics: fast time response, ultra broadband, operation at ambient temperatures, and structures simplicity; MOM diodes have remained in the laboratory level as a result of their inherent mechanical, electrical and heating effect instabilities. Attempts to remove the instability from the free-standing long wire configuration and the sharp tip through printed circuits techniques have yet to prove successful.

In this paper, we demonstrate results which ask for re-examination of the MOM diode theoretical modeling, enhance the possibility of the MOM diode for field applications and call for further feasibility study of this inexpensive device.

In the past, the whisker tip was assumed to remain pointed after penetration into the oxide layer and theoretically analyzed on that basis. We have found that, for stable detection, the whisker tip should not remain pointed, rather a hooked contour structure proves to be able to overcome or reduce most of the instabilities.

We will thus report here the sequence of events that leads to this conclusion: the painstaking fabrication study that has often been overlooked by workers in this area and the critical tests of this device at X-band, V-band and in the infrared that shed light on the ultimate stable configuration.

MOM Point Contact Diode Fabrication

The MOM point contact diode consists of a tungsten whisker and a nickel post with a naturally grown thin oxide layer. The whisker tip is etched from 25μm tungsten wires by the standard electrolytic technique, where the wire is dipped into a 2N KOH solution and an ac voltage is applied. This etching process is carefully monitored in terms of the voltage across the electrodes, the immersion depth of the tungsten wire solution and the etching time. The wire is etched at various voltages, and immersion depths. The etched conical shape is found to depend on the depth of immersion, applied voltage across the etching resistance, conductivity variations resulting from etched out deposits and the geometry of the electrodes.

MOM Point Contact Diode Testing Structure and Procedure

The whisker is silver cemented to a mount, which is attached to a differential micrometer for movement to make contact with the oxide layer on the nickel post. Contact is monitored via the I-V curve of the diode.

At X-Band

The first experiments were performed at X-band for convenience and familiarization with this diode. The microwave sources are tunable, and one was modulated and used for detection. This diode was irradiated by the microwave radiation emerging from the end of an open waveguide at a short distance away. The differential micrometer was advanced until contact was made as witnessed on the I-V curve tracer. The detected output was displayed on a standard scope, somewhat stabilized by fine adjustment of the micrometer. Detection had at best short-term stability and polarity reversal was frequent and unpredictable.

Once signal was somewhat stabilized, radiation from another X-band source was piped in for mixing. The beat of 1 GHz which was quite easily demonstrated on the scope. Initial tuning was assisted by a 1 GHz B.W. spectrum analyzer.

Most of the steps with obvious modifications are followed for experiments at other frequencies. No attempts were made to form a hook at this stage.

Infrared Detection

The beam of a 3.0 watts CO_2 laser at 10.6μm was chopped and focused onto the MOM point contact diode. Illumination was optimized as to antenna properties by the xyz-θ manipulation of the microtranslation stage.

Initially, the detected response was high and unstable. The whisker used in this test had been etched to be short and sharp as in the case of the X-band. After long unsuccessful attempts to stabilize the signal with these whiskers, we finally turned to long, slender and sharp whiskers. As the whisker penetrated the oxide layer, and contact pressure was increased, a stable though non-square wave response was observed. Encouraged by this relatively long-term stable detection, whiskers were etched carefully by controlling the immersion depth and applied voltage to achieve a slender and sharp whisker. In repeated tests stable detection was observed and square wave response was possible by varying contact pressure. The signal was optimized, and was observed to follow the speed of the chopper. The whisker was examined and found, without exception, to have acquired a hook contour. Variations in hook contour are possible if the fabrication

process is not carefully controlled. We are thus led to believe that we must find an optimum slender ratio (the ratio of shaft length to tip size). This ratio is the governing factor of the eventual hook contour following tip penetration into the oxide layer. There is trade off between stability and responsivity only in the sense when the tip is excessively hooked because of too slender a shaft, resulting in insufficient penetration of the oxide layer and excessively large contact area.

The improvement in stability once the hook was formed was dramatic. We have yet no long-term stability data (over days or months), but our rather casual handling of the diode mount and repeated observation of stable detection with a hooked tip, were convincing evidence of possible long-term stability.

V-Band Detection And Mixing

For mixing experiments with significant bandwidth, say 10 GHz, we resorted to the V-band. The experimental setup was based on 3 frequency mixing since we only had a 1GHz spectrum analyzer. The experimental scheme is similar to that for the X-band. V-band signal was first modulated and detected by the MOM diode. When stable detection was achieved, the mixing experiment was performed with the two V-band sources at 7 GHz apart, which in turn was beat with X-band radiation to yield a MHz signal detected on standard scope.

Discussion And Conclusion

Previously assumed undesirable features of the MOM point contact diode are: free-standing, long-wire and sharp tip, the former leading to susceptibility to vibrations, and the latter to electrical and heating effects. However, the long-wire antenna feature is very desirable.

The hooked whisker tip automatically provides spring action that cushions mechanical vibrations and the free sharp tip, still providing good biconical antenna property, allows heat expansion and keeps the excessively high electrical fields from the junction area.

There is a slender ratio for optimum response and stability and this can be reproduced by careful monitoring of the etching process.

Another very interesting fall-out of our efforts so far is the confirmation that present antenna models based on the biconical antenna is not practical and we suspect that revisions must also be made in the diode modeling.

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